WIND TUNNEL WALL CORRECTIONS FOR ARBITRARY PLANFORMS AND WIND TUNNEL CROSS-SECTIONS

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THESIS

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by

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Wind Tunnel Wall Corrections for Arbitrary Planforms and Wind Tunnel Cross-Sections

by

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Lieutenant, United States Navy
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ABSTRACT

A computer program was developed to obtain the wind tunnel wall corrections for wing angle of attack, induced drag, and pitching moment in incompressible flow. The vortex lattice method is used for computation of these correction factors. The program can be applied to wind tunnels of arbitrary cross-sectional shape, and wings of any desired planform, subject to the constraint of straight leading and trailing edges.

TABLE OF CONTENTS

I. INTRODUCTION ---------------------------------- 12

II. METHODS USED ---------------------------------- 15

A. GENERAL ---------------------------------- 15

B. VORTEX LATTICE METHOD -------------------- 17

C. AIRFLOW REPRESENTATION ------------------- 20

D. DETERMINATION OF WALL CORRECTIONS -------- 24

III. RESULTS AND DISCUSSION ---------------------- 30

A. THE COMPUTER PROGRAM --------------------- 30

B. GROUND EFFECT ---------------------------- 31

C. WIND TUNNEL APPLICATION ------------------ 34

IV. CONCLUSIONS AND RECOMMENDATIONS -------------- 43

APPENDIX A: ASSUMPTIONS -------------------------- 44

APPENDIX B: DEVELOPMENT OF INDUCED VELOCITY EQUATIONS -------------------- 45

APPENDIX C: COMPUTER PROGRAM INPUT --------------- 50

COMPUTER PROGRAM --------------------------------- 51

LIST OF REFERENCES ------------------------------- 74

INITIAL DISTRIBUTION LIST ------------------------ 75

LIST OF FIGURES

1. Wind Tunnel Geometry ---------------------------- 18

2. Wing Geometry ----------------------------------- 22

3. Ground Effect Ratio Plotted as a Function of Wing Height Above the Ground --------------- 32

4. Wing Span Load Distribution -------------------- 35

5. Induced Drag Distribution ---------------------- 39

6. Angle of Attack Correction Factor Plotted as a Function of Span Ratio ------------------- 40

7. Angle of Attack Correction Factor Plotted as a Function of Sweep Angle ------------------ 41

8. Velocity Induced by a Vortex Segment ---------- 46

LIST OF TABLES

1. Ground Effect Factor Variation With Sweep Angle ---------------------------------- 33

2. Wing Parameter Variation with Span ----------- 36

3. Wing Parameter Variation with Sweep Angle ---------------------------------- 37

LIST OF SYMBOLS

[AERO]	Wing aerodynamic influence coefficient matrix at the 0.75 chord position
AR	Wing aspect ratio = b^2/S
b	Wing Span
C	Wind tunnel cross-sectional area
c	Local wing chord, streamwise direction
c_{ave}	Average wing chord, (s/b)
$c_\ell c$	Wing span loading, (ℓ/q)
C_L	Wing lift coefficient = Lift/qS, dimensionless
$C_{L_{\alpha_g}}/C_{L_{\alpha_{Fa}}}$	Ground effect ratio
C_m	Pitching moment coefficient = Moment/$qS\bar{c}$
C_R	Root chord
C_T	Tip chord
C_{D_i}	Wing induced drag coefficient
$C_d c$	Spanwise induced drag distribution (d/q)
d	Wing induced drag distribution, drag/unit span
[DAERO]	Wing aerodynamic influence coefficient matrix at the wing quarter-chord
[GAMAL]	Wall vortex loop strength
h	Wing height above the ground
H	Wind tunnel height
ℓ	Wing running span load, lift/unit span
NS	Number of horseshoe vortices per semispan
q	Dynamic pressure

[ROL]	Wall aerodynamic influence coefficient matrix
[ROT]	Influence coefficient matrix for wall-on-tail
[ROW]	Influence coefficient matrix for wall on wing
S	Wing area
TR	Wing tape ratio, C_T/C_R
V	Freestream velocity
w	Induced downwash velocity
W	Wind tunnel width
$(\frac{w}{V})_{3c/4}$	Induced downwash angle at 0.75 chord position
[WOL]	Influence coefficient matrix for wing-on-wall
[WOT]	Influence coefficient matrix for wing-on-tail
X	Axial coordinate
Y	Vertical coordinate
Z	Spanwise coordinate
α	Angle of attack
δ	Wind tunnel wall interference factor
Γ	Vortex strength
ε	Induced downwash angle at the tail
η	Wing spanwise stations $(\frac{2Z}{b})$
η_{TL}	Tail efficiency factor

Subscripts:

FA	free air
g	ground
ℓ	wall vortex loops
T	wind tunnel

TL	tail
w	wing
$(\ )_{\alpha}$	$\partial(\ )/\partial\alpha$

Matrix Notation:

[ ]	Rectangular matrix
{ }	Column matrix
$\lceil\ \rfloor$	Diagonal matrix
$[\ ]^{-1}$	Inverse of a square matrix

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I. INTRODUCTION

In the process of wind-tunnel testing the experimental procedure itself constrains and alters the flow past the wing under examination. This modified flow induces errors which must be corrected if accurate results are to be obtained. The major interference effects in subsonic wind tunnels result from the constraining influence of wind tunnel walls, disturbances from model supports and measuring equipment, and turbulence and non-uniformity in the airflow itself.

Russell [Ref. 10] treats the problems resulting from model support interference and introduces a method for reduction of this effect. The differential equations governing flow within a wind tunnel are the same as those in free air. However, the presence of the wind tunnel walls changes the outer boundary conditions. The result is a series of perturbations of the velocity-potential gradient normal to the model surface. The effect is pervasive in that almost all of the measured aerodynamic quantities must be corrected.

Generally, Prandtl is acknowledged as having established the foundations for research on wind-tunnel wall interference. His lifting-line theory and concept of trailing vortices opened the doors to much experimental investigation in this area. The resulting studies considered two-dimensional

and three-dimensional effects, open and closed wind tunnels, and various geometrically shaped test sections.

References 1 and 8 offer a comprehensive treatment of wind-tunnel wall interferences. Much tabular and graphical data are presented for different tunnel shapes and wing spans. Pankhurst and Holder included much data on octagonal wind tunnels, while Pope concentrated more on a uniformly loaded wing.

With the advent of sweptback, slender wings designed for high-speed flight, the lifting line model was no longer suitable. In these situations, the wing lifting system may be represented by distributed horseshoe vortex elements [Refs. 6 and 7]. In Ref. 9, data, graphs, and formulas are easembled from various sources and systematically analyzed for various types of wings in wind tunnels. Although the mathematical formulations are tedious, the resulting graphs and tables summarized very well the data obtained from each theoretical treatment.

Even with all this information available, it is still an arduous task to approach tabulated data with a specific wind tunnel shape and geometric configuration, and hope for a solution to the wall interference problem. It is the purpose of this paper to develop a computerized, closed-form solution to this problem. The design goal was to develop a digital computer code that would be applicable to wind tunnels of arbitrary cross-section and wings with

varying planforms. Such versatility would enhance the accuracy of test data and provide a valuable, accurate tool in wind-tunnel testing.

II. METHODS USED

A. GENERAL

Wind tunnels provide an invaluable tool in the design and performance prediction of wings and wings-and-bodies. However, the wind-tunnel testing environment introduces its own set of problems. The interference action from the walls of the wind tunnel alters the development of induced velocities by the wing lifting system. As a result, downwash formation is suppressed and the wing aerodynamic characteristics are those of a wing having greater aspect ratio. The accurate determination of wind tunnel wall interference is, therefore, an important consideration in wing experiments.

The classical wall correction factor, δ, for the case of a single horseshoe vortex representing the complete wing is defined by:

$$\Delta\alpha = \delta \frac{S}{C} C_L \qquad (1)$$

where

$$\Delta\alpha = \tan^{-1} \frac{w}{V}$$

Using small angle approximations, the tangent is approximately equal to the angle. The wall-correction factor may be expressed in terms of wing circulation, vortex span and average induced downwash velocity by:

$$\delta = \frac{w}{2b}\frac{c}{\Gamma_w} \tag{2}$$

Calculation of δ is dependent on the determination of the downwash velocity induced by the wind tunnel walls. Classical methods involve the utilization of an image system of vortices which cancel the effect of the wing lifting system at the wall. The boundary condition of no flow through the wall is, therefore, preserved. This system can provide an accurate, closed-form solution to the ground effect problem. However, when four walls are present, each wall must be represented by an image system which affects other image systems, as well as the model itself. The result is a series of infinite systems. Truncation of this system introduces inaccuracies of unknown magnitude and significance.

This method of images has been applied to tunnels of rectangular cross-section with success. However, it is inadequate when arbitrary tunnel cross-sections are encountered. Add to this a wing with sweep and taper, and the problem becomes significantly altered.

Therefore, a new method was sought to solve this problem specifically for the NPS 3.5 X 5 ft. octagonal wind tunnel. The technique chosen was presented by Joppa in Refs. 4 and 5. This approach lends itself very well to computer solution and can be applied to wind tunnels of any cross-sectional shape.

In this study, an extension of Joppa's vortex lattice method was made to allow the treatment of wings with varying shape, sweep, and aspect ratio. Such treatment requires a modification of the single horseshoe vortex representation of the wing lifting system. The method of Weissinger as presented in Ref. 6 provides an accurate means of representing variable planforms.

B. VORTEX LATTICE METHOD

Since the method of images was considered to be limited in application, it was necessary to find another, more versatile method of representing the wind-tunnel walls. The problem is essentially one of finding a vorticity distribution which will accurately model the wind-tunnel walls. This vortex system must satisfy the boundary condition of no flow through the walls.

In Ref. 4, Joppa presents a method which accurately models the wind-tunnel walls. This was accomplished by representing the tunnel walls with a lattice network of rectangular vortex loops. This vortex system lies in the plane of the tunnel walls and satisfies Helmholtz's theorem that a vortex filament can neither begin nor end in the flow. Fig. 1 shows a representation of this system as applied to the NPS 3.5 by 5 ft. wind tunnel.

Each vortex segment in a given rectangle has vortex strength Γ_i, and has a corresponding control point located

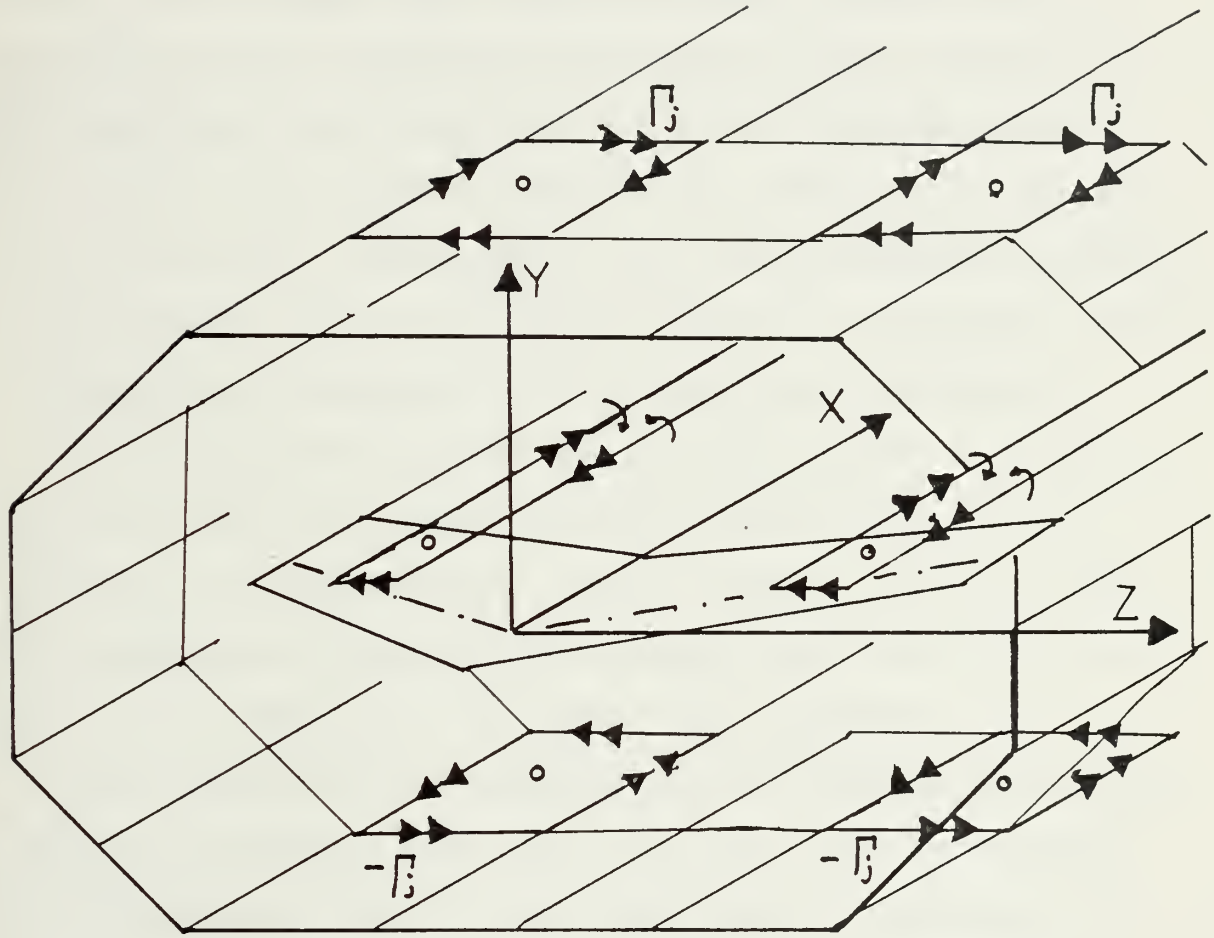

Figure 1. Wind Tunnel Geometry

in the center of each rectangle where the no-flow boundary condition is satisfied. The last vortex lattice rectangles located far downstream are represented by horseshoe vortices trailing to infinity. The reasoning is that far downstream, where the influence upon the wall vortex lattice array of the bound vortex elements on the wing is small relative to the trailing vortex elements, one finds that the vortex strengths of the lattice terms do not change in the streamwise direction. Consequently, by a straightforward cancellation argument, one can visualize replacing the vortex lattice rectangles by horseshoe vortices trailing to infinity.

The mathematical presentation of the theory is based on the Biot-Savart law describing the velocity induced at a point by a vortex segment. Joppa in Refs. 4 and 5 follows the mathematical formulation beginning with the Biot-Savart law. This development is summarized in Appendix B.

The general matrix representation of this method centers around the boundary condition of no flow through the wall. As mentioned previously, this condition is satisfied at a control point located at the center of each vortex loop. Therefore, it follows that the velocity induced at each control point by the vortex loops must be exactly cancelled by the velocity created by the wing lifting system. This is presented below in matrix representation

$$[ROL]\ \{\Gamma_L\} = [WOL]\ \{\Gamma_W\} \tag{3}$$

which allows a solution of vortex lattice strengths in terms of the wing vortex strengths.

$$\{\Gamma_L\} = [ROL]^{-1} [WOL] \{\Gamma_w\} \quad (4)$$

Note that the [ROL] matrix, although possibly quite large, is square and hence may be inverted.

[ROL] represents the wall influence coefficient matrix. It is obtained by calculating the downwash induced at each wall control point by a unit value of each vortex loop. Therefore, ROL_{ij} is the downwash at wall control point "i" induced by vortex loop "j". [WOL] is the influence coefficient matrix describing the wing effect on each loop control point. WOL_{ij} is the downwash produced at control point "i" by the j^{th} wing horseshoe vortex.

By inverting [ROL] and premultiplying with [WOL], the strength of the wall vortex loops can be found in terms of the wing circulation. The inversion of [ROL] can be very time-consuming, since it may be a very large matrix. However, by using symmetry, the order of this matrix can be reduced by a factor of four. This requires the wing to be placed on the horizontal and vertical centerline of the wind tunnel.

C. AIRFOIL REPRESENTATION

In Ref. 5, Joppa stated that the wing can be represented by a lifting system more complicated than a single

elementary horseshoe vortex. In order to model swept wings of arbitrary planform, a more definitive lifting system model was employed. Gray and Schenk, Ref. 6, present a modified Weissinger method designed to find the load distribution of wings with arbitrary planform. The wing is represented by a series of horseshoe vortices. The midspan of each horseshoe vortex bound element is located at the wing quarter-chord position. The condition of flow tangency is satisfied at the wing three-quarter-chord point in the center of each horseshoe vortex. Figure 2 illustrates the configuration chosen.

Pearson [Ref. 7] modified this technique by allowing the bound vortices to be swept, and including chord-wise horseshoe vortices. For this presentation it was felt that unswept bound vortices would accurately represent the lifting system of a swept wing. In addition it was felt that little deterioration of accuracy would result if the chordwise system of bound vortices was combined into a single bound vortex at the quarter-chord. Figure 2 illustrates the configuration chosen.

An important concept in this representation of the wing is that of flow tangency at the three quarter-chord. The downwash angle at the wing can, therefore, be determined by placing a control point at this position in the center of each horseshoe vortex. The rationale behind the three-quarter chord flow tangency condition is a product of

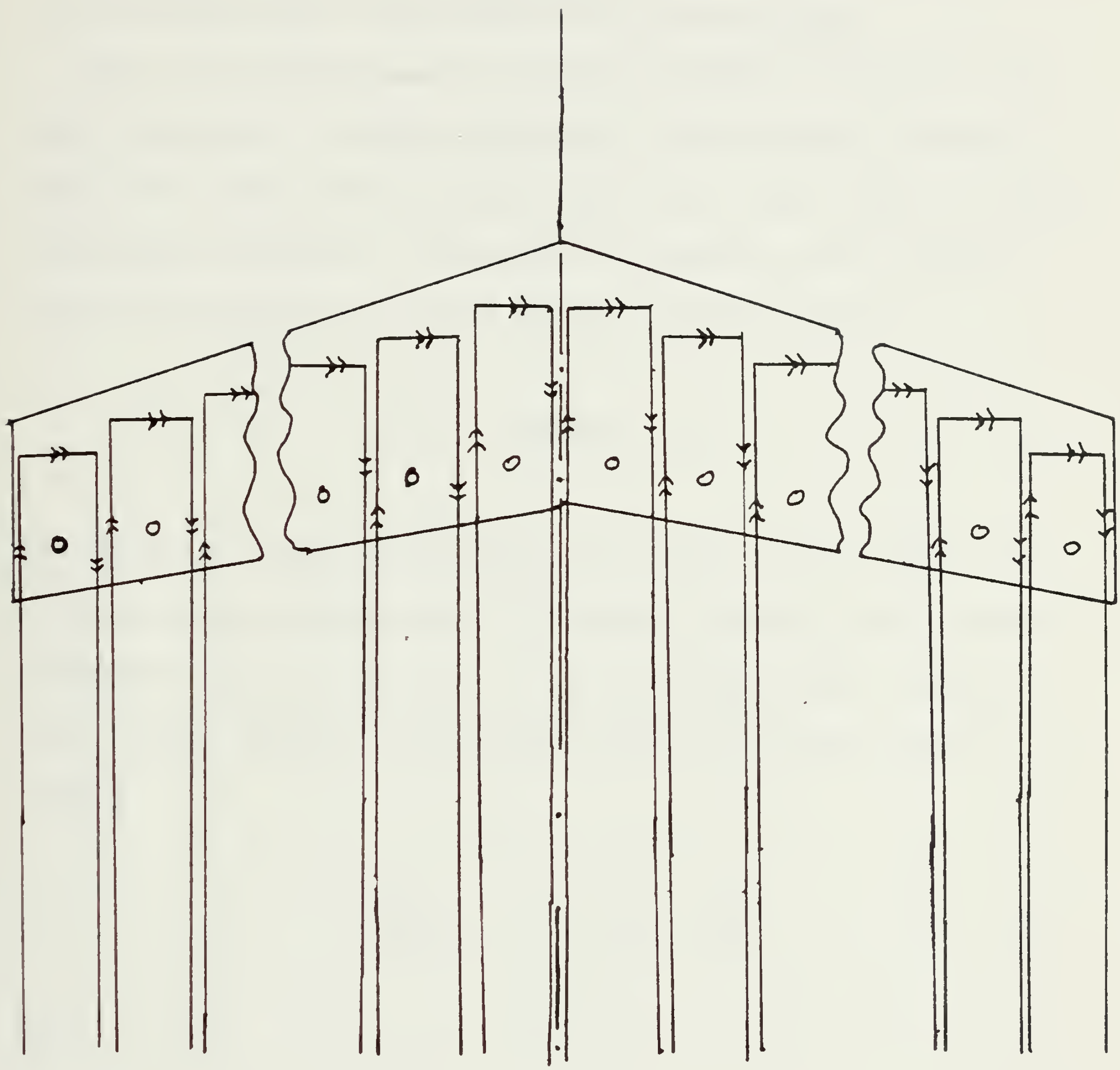

Figure 2. Wing Geometry

two-dimensional flow considerations. Extension of this technique to the three-dimensional wing has been shown to produce experimentally confirmed results. However, it is still unclear why this technique works so well.

The wing aerodynamic influence coefficient matrix was then developed. [AERO] represents the downwash induced at each 0.75 chord wing control point by a unit value of wing horseshoe vortices. The matrix formulation for induced downwash formation in free air is presented below:

$$\{w\} = [AERO]\ \{\Gamma_w\} \tag{5}$$

Dividing the above expression by freestream velocity, one obtains an expression for 0.75 chord control point induced downwash angles. The flow tangency requirement equates this column matrix to the wing angle of attack column vector.

$$\left\{\frac{w}{V}\right\}_{3c/4} = [AERO]\ \left\{\frac{\Gamma}{V}\right\} \tag{6}$$

and

$$\{\alpha\} = \left\{\frac{w}{V}\right\}_{3c/4}$$

It should be noted here that $\frac{\ell}{q}$ is equal to $\frac{2\Gamma}{V}$, from the Kutta-Joukowski Law. Substitution into equation 6 yields the following results:

$$\left\{\frac{w}{V}\right\}_{\frac{3c}{4}} = 0.5\ [AERO]\ \left\{\frac{\ell}{q}\right\}_{FA} \tag{7}$$

Solving equation 7 for $\{\frac{\ell}{q}\}$, one can obtain the wing span load distribution. Since $\frac{\ell}{q}$ is equivalent to the sectional value of $C_\ell c$, integration of the $\frac{\ell}{q}$ distribution vs. span provides a direct measure of the wing lift coefficient, C_L. When one assumes a uniform angle of attack value of one radian along the span, the resultant integration of the span load solution will yield the wing lift curve slope, $C_{L\alpha}$. It should be borne in mind that these techniques are predicated upon principles from thin airfoil theory and in the limit for an infinite aspect ratio wing will yield a wing lift curve slope of $2\pi(\text{rad}^{-1})$.

D. DETERMINATION OF THE WALL CORRECTIONS

The classical wall interference factor δ, which includes a ratio of wing to tunnel cross-section area, is generally found by representing the wing as a single horseshoe vortex. Since the present formulation utilizes ten horseshoe vortices per semi-span, δ in a modification can best be found by continuing our matrix algebra.

$$\alpha_{FA} = \alpha_T + \delta C_L$$

$$\alpha_{FA} = \frac{C_L}{C_{L_{\alpha_{FA}}}} \tag{8}$$

$$\alpha_T = \frac{C_L}{C_{L_{\alpha_T}}}$$

By assuming that the lift coefficient is the same in both tunnel and free air, the following equations result:

$$\frac{C_L}{C_{L_{\alpha_{FA}}}} = \frac{C_L}{C_{L_{\alpha_T}}} + \delta\, C_L \tag{9}$$

Cancelling the lift coefficient and solving for δ:

$$\delta = \frac{1}{C_{L_{\alpha_{FA}}}} - \frac{1}{C_{L_{\alpha_T}}} \tag{10}$$

The free air lift slope was found in the previous section. The wing lift curve slope for the wing in the wind tunnel can be found by a simple extension of this same method. The total downwash at the wing control points is equal to that induced by the wing added to that created by the tunnel walls. The effect produced by the tunnel walls is represented by the vortex rectangle-on-wing influence coefficient matrix [ROW]. ROW_{ij} is the downwash induced at the i^{th} wing control point by the j^{th} wall vortex loop. Multiplying this matrix by the vortex loop strength, one obtains the total wall effect.

$$\{w\} = [AERO]\ \{\Gamma_W\} + [ROW]\ \{\Gamma_L\} \tag{11}$$

Substitution of equation 4 for $\{\Gamma_L\}$ forms the following set of equations:

$$\{w\} = [AERO]\ \{\Gamma_w\} + [ROW]\ [ROL]^{-1}\ [WOL]\ \{\Gamma_w\}$$

$$\{\frac{w}{V}\}_{\frac{3c}{4}} = 0.5\ [[AERO] + [ROW][ROL]^{-1}[WOL]]\{\frac{\ell}{q}\}_T \qquad (12)$$

By establishing one radian angle of attack, solving for $\frac{\ell}{q}$, and integrating the result, the wind-tunnel lift curve slope can be determined. It should be noted that the correction factor obtained from this process is different from the classical δ, since the correction factor computed above already contains the wing area to tunnel area ratio influence. Therefore, the correction to angle of attack can be obtained by a direct application of this δ.

$$\Delta\alpha = \delta\ C_L \qquad (13)$$

In most literature, the correction for induced drag is obtained by application of the same δ as that used for angle of attack.

$$\Delta C_{D_i} = \delta\ C_L^{\ 2} \qquad (14)$$

However, in this presentation, the induced drag correction is calculated in a different manner because of added available aerodynamic information. The spanwise induced drag distribution in free air is given by the following formula:

$$\left\{\frac{d}{q}\right\}_{FA} = \left\lceil \frac{\ell}{q} \right\rfloor_{FA} [DAERO] \left\{\frac{\ell}{q}\right\}_{FA} \qquad (15)$$

[DAERO] is the wing aerodynamic influence coefficient matrix computed with the wing control point now located at the quarter-chord position. The wall effect can similarly be found by including additional matrix terms for the wall effect on the wing quarter-chord position.

$$\left\{\frac{d}{q}\right\}_{T} = \left\lceil \frac{\ell}{q} \right\rfloor_{T} [[DAERO] + [ROW][ROL]^{-1}[WOL]]\left\{\frac{\ell}{q}\right\}_{T} \qquad (16)$$

Integration of equations 15 and 16 result in the free air and wind tunnel induced drag, respectively. The induced drag correction factor can then be found in the following manner.

$$C_{D_{i_{FA}}} = K_{FA}\, C_{L_{FA}}^{2}$$

$$C_{D_{i_{T}}} = K_{T}\, C_{L_{T}}^{2}$$

$$K_{FA} = C_{D_{i_{FA}}} / C_{L_{FA}}^2$$

$$K_T = C_{D_{i_T}} / C_{L_T}^2 \qquad (17)$$

$$K = K_{FA} - K_T$$

$$\Delta C_{D_i} = K\, C_{L_T}^2$$

When testing a model in the tail-on configuration, the presence of the wind tunnel walls serves to modify the downwash angle induced at the tail. This altered flow field can have a significant effect on the pitching moment coefficient. The following increment in pitching moment coefficient is generated by the horizontal tail:

$$\Delta C_{m_{TL}} = \left(\eta_{TL} \frac{S_T\, \ell_{TL}}{S_w\, c}\, C_{L_{\alpha_{TL}}}\right) \alpha_{TL} \qquad (18)$$

The term in parentheses is approximately equal to the stabilizer effectiveness, $\frac{\partial C_m}{\partial \delta_i}$. The tail angle of attack can be estimated as follows:

$$\alpha_{TL} = \alpha - \varepsilon + \delta_i \qquad (19)$$

At a given value of wing lift coefficient an incremental change in downwash angle at the tail due to the wall effect can be computed:

$$\Delta\varepsilon = \varepsilon_T - \varepsilon_{FA} \tag{20}$$

Therefore, the correction to pitching moment coefficient is given by the following relation:

$$\Delta C_m = C_{m_i} \Delta\varepsilon \tag{21}$$

Since the downwash angle ε is equal to $\frac{w}{V}$ at the tail position, ε for free air and for the wind tunnel can be found from the following relations, respectively:

$$\varepsilon_{FA} = 0.5[WOT] \{\frac{\ell}{q}\}_{FA}$$

$$\varepsilon_T = 0.5[[WOT] + [ROT][GAMAL]] \{\frac{\ell}{q}\}_T \tag{22}$$

[WOT] is the wing effect on the tail position and [ROT][GAMAL] represents the wall effect on the tail. Equation 20 can then be used to find $\Delta\varepsilon$. The pitching moment correction, as evaluated in equation 21, is thus dependent on being given an experimental value for the tail effectiveness parameter.

III. RESULTS AND DISCUSSION

A. COMPUTER PROGRAM

The computer program developed consists of two major subroutines. Subroutine Loop calculates the downwash at any point due to a vortex rectangle. Subroutine HSHOE computes the downwash at any arbitrary point due to a horseshoe vortex. HSHOE is used for both the wing horseshoe and those of the wall system located far downstream in the tunnel walls. The program offers two basic options. One option establishes whether ground effect or wind-tunnel wall corrections are to be calculated. The other option indicates whether the tail-on or tail-off case is to be considered.

Each computer run offers the inclusion of many wings of different span, aspect ratio, taper ratio, and sweep. The wing parameters are read as input data after the inversion of the large wall-on-wall coefficient matrix. Therefore, with a given tunnel configuration, a variety of different wings can be included with a minimum of computer time consumed.

Integration of the wing span loads in accomplished by a subroutine obtained from the NPS source library. It should be noted that in the integration scheme the assumption is made that the wing loading at $\eta = 0.0$ is the same as that for $\eta = .05b$. Any inaccuracy resulting from this assumption

appears to be negligible. Appendix C describes the necessary input to the program.

B. GROUND EFFECT

Originally, ground effect calculations were conducted merely to check the accuracy of the vortex lattice method. As previously stated, the method of images provides a closed-form solution to the ground effect problem. Therefore, this provided an excellent opportunity for a convergence check. As an object of academic interest an option for ground effect computation was retained in the final computer program.

The results of the convergence check showed that the vortex lattice method could very accurately compute the velocity induced at a point by the presence of a wall. By applying the theory previously developed, the lift curve slopes for free air and ground effect were computed. Results were then compared with those presented in Etkin [Ref. 3]. The free air lift curve slope was found to correlate extremely well for both straight and sweptback wings.

Furthermore, in Ref. 3, Etkin defines a ground effect ratio as the ground effect lift curve slope divided by that in free air. The results are tabulated in Table 1, and Figure 3 compares the results obtained from the computer program with those presented in Etkin. As can be seen, agreement is very favorable.

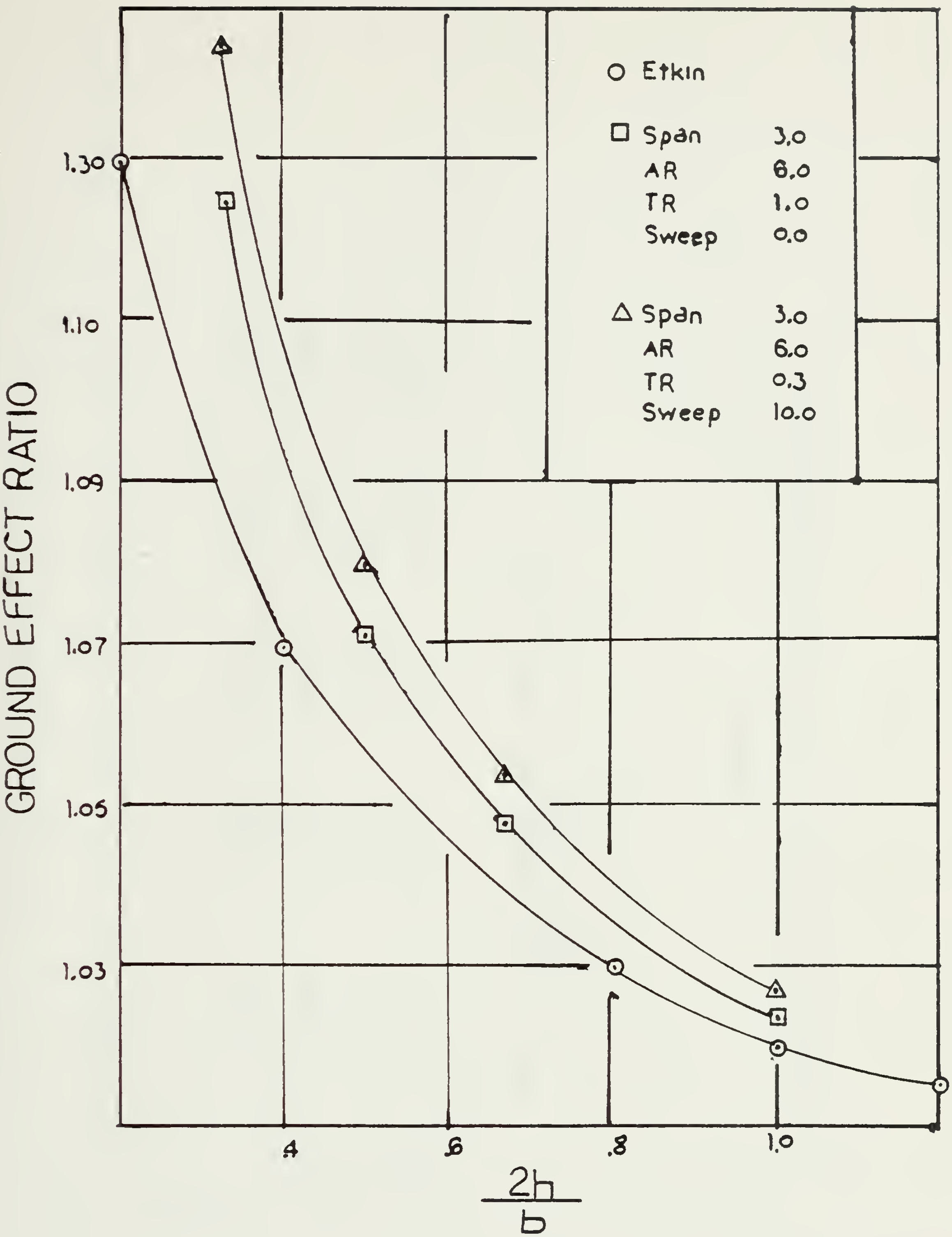

Figure 3. Ground Effect Ratio Plotted as a Function of Wing Height Above the Ground

	0.25 Chord Sweep Angle, deg				
$\frac{2h}{b}$	0.0	10	20	30	40
1.0	1.0248	1.0266	1.0259	1.0244	1.022
.667	1.0488	1.0541	1.0521	1.0481	1.0426
.50	1.072	1.080	1.079	1.073	1.065
.333	1.126	1.145	1.139	1.125	1.01

Note: Values apply to a wing with
AR = 6.0
TR = 0.3

Table 1

Ground Effect Factor Variation with Sweep Angle

Several computer runs were conducted at different wing heights above the ground. For each run, sweep was varied from 0 to 40 degrees. Results are tabulated in Figure 4. It can be noted that the ground effect ratio initially increases with sweepback but returns to the unswept value at about 30 degrees.

As a note of caution, care should be exercised when the wing gets very close to the ground. It is necessary to greatly decrease the vortex loop size for accurate results. This procedure seems to provide a much more finely defined ground representation. Otherwise, calculations will result in inordinately high values.

C. WIND TUNNEL APPLICATION

A convergence check of the wind tunnel wall correction factor was obtained by applying the program to a 3 X 5 ft rectangular tunnel. The correction factor obtained was converted to the classical δ by including the factors $\frac{S}{C}$ and 57.3 (radians to degrees). The result of 0.1216 was compared to that presented by Joppa in Ref. 5. The wing geometric configuration presented in Ref. 5 consisted of a single horseshoe vortex. The value of 0.127 from Ref. 5 correlates very well with the results of this study.

Tables 2 and 3 present the data obtained from computations with the NPS 3.5 X 5.0 ft octagonal wind tunnel. Computer runs were conducted using wings of varying span

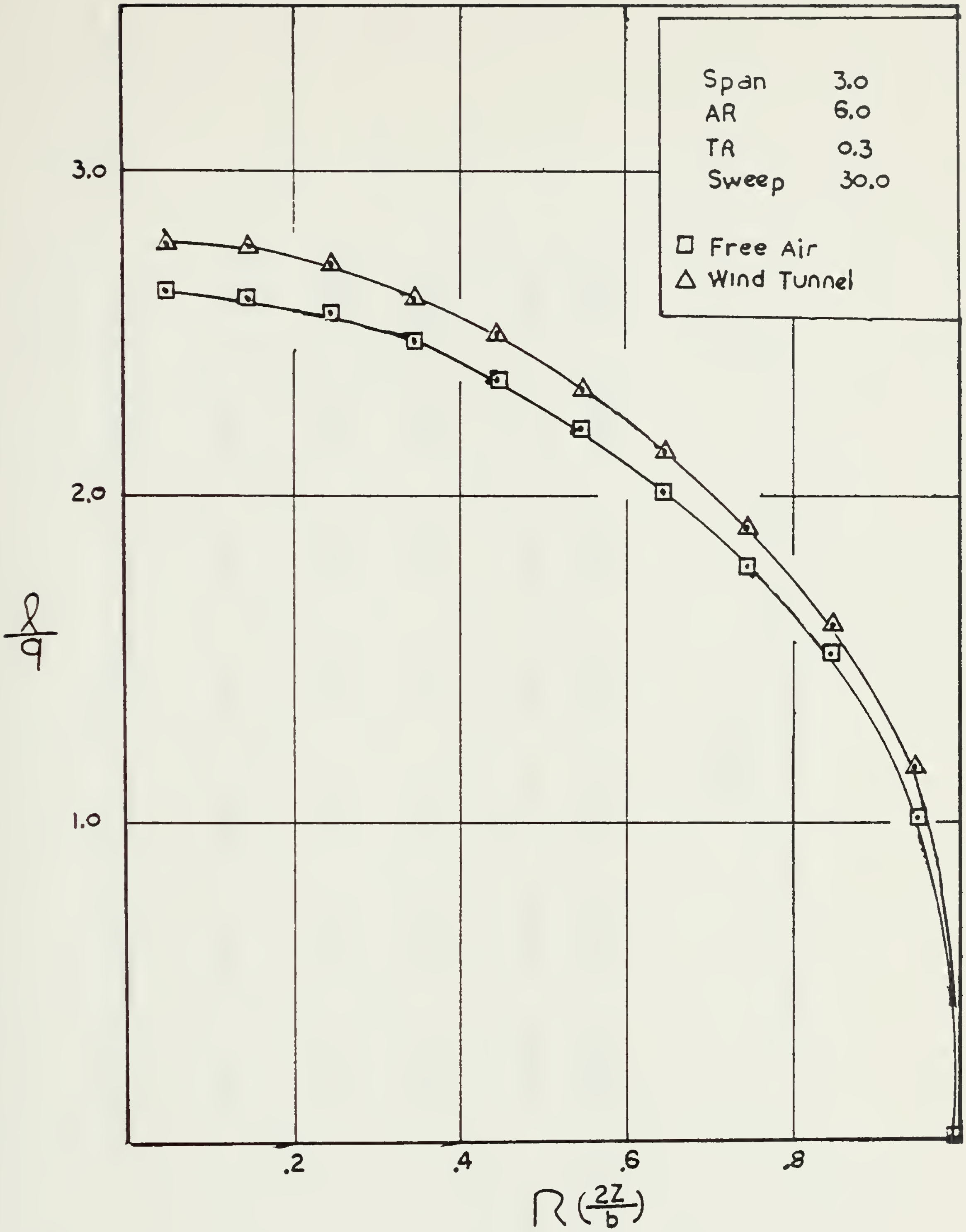

Figure 4. Wing Span Load Distribution

SPAN RATIO	.4	.5	.6	.7	.8	.9	.10
$C_{L_{\alpha_{FA}}}$	4.2545	4.2545	4.2545	4.2545	4.2545	4.2545	4.2545
$C_{L_{\alpha_T}}$	3.354	4.4135	4.4907	4.594	4.7489	5.6563	6.2838
$C_{D_{FA}}$	.9342	.9342	.9342	.9342	.9342	.9342	.9342
C_{D_T}	.8855	.8583	.8240	.7793	.7145	.5904	-.003
$\Delta\alpha$ Correction	.30799	.48539	.7086	.9955	1.4022	2.1358	4.3493
ΔC_D Correction	.0049	.00755	.0107	.0147	.0199	.0285	.0517

Table 2

Wing Parameter Variation With Span

c/4 Chord Sweep	0	5	10	15	20	25	30	35	40
$C_{L_{\alpha_{FA}}}$	4.2545	4.3929	4.3816	4.3479	4.290	4.205	4.09	3.9401	3.7505
$C_{L_{\alpha_T}}$	4.4907	4.6475	4.6347	4.5966	4.5312	4.4355	4.3062	4.1388	3.9285
$C_{D_{FA}}$	.9342	.9948	.9924	.9806	.9585	.9252	.8796	.8208	.7480
C_{D_T}	.824	.882	.8799	.8694	.8494	.8190	.7773	.7235	.6570
$\Delta\alpha$ Correction	.7086	.7144	.7141	.7129	.7107	.70754	.7035	.69845	.69197
ΔC_D Correction	.0107	.01073	.01072	.01072	.01071	.01069	.01066	.01064	.01061

Table 3

Wing Parameter Variation with Sweep Angle

and sweep angle. Figures 4 and 5 illustrate the span loads calculated for a typical wing. It is interesting to note that as sweep angle increased, negative induced drag appears on the outboard wing stations. Therefore, total induced drag is seen to steadily decrease with increasing sweep angle.

As sweep angle is increased, the free air lift curve slope decreases. Correspondingly, the corrections to angle of attack and induced drag are reduced. Figure 6 graphically displays the data for a straight wing. In the past, the correction factors for the NPS 3.5 X 5.0 ft octagonal wind tunnel were obtained by assuming an elliptic cross-section. The correction factors presented in Ref. 1 for elliptic cross-section are 0.610 for angle of attack and 0.0106 for induced drag. In comparison, the vortex lattice program computes values of 0.7086 and 0.01075, respectively. It is interesting to note that the induced drag correction is almost identical, whereas the correction to angle of attack is slightly higher for the octagonal wind tunnel. Figure 7 illustrates the angle of attack correction factor with varying tunnel span ratios. The correction factor can be seen to steadily increase with the span ratio.

It is an interesting observation that the value of induced drag for a wing span of 5.0 ft was almost zero. This compares very well with airfoil theory in that a wing

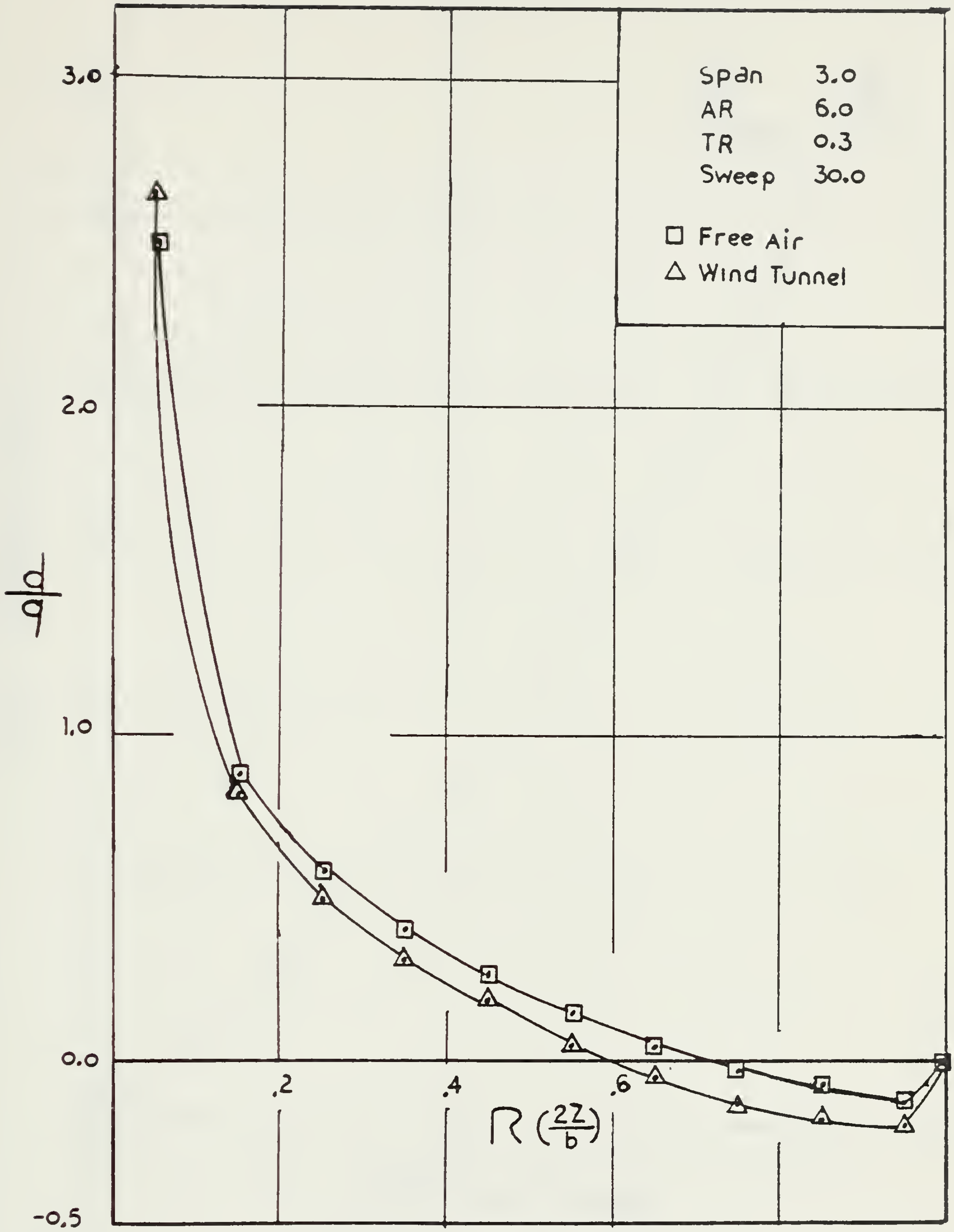

Figure 5. Induced Drag Distribution

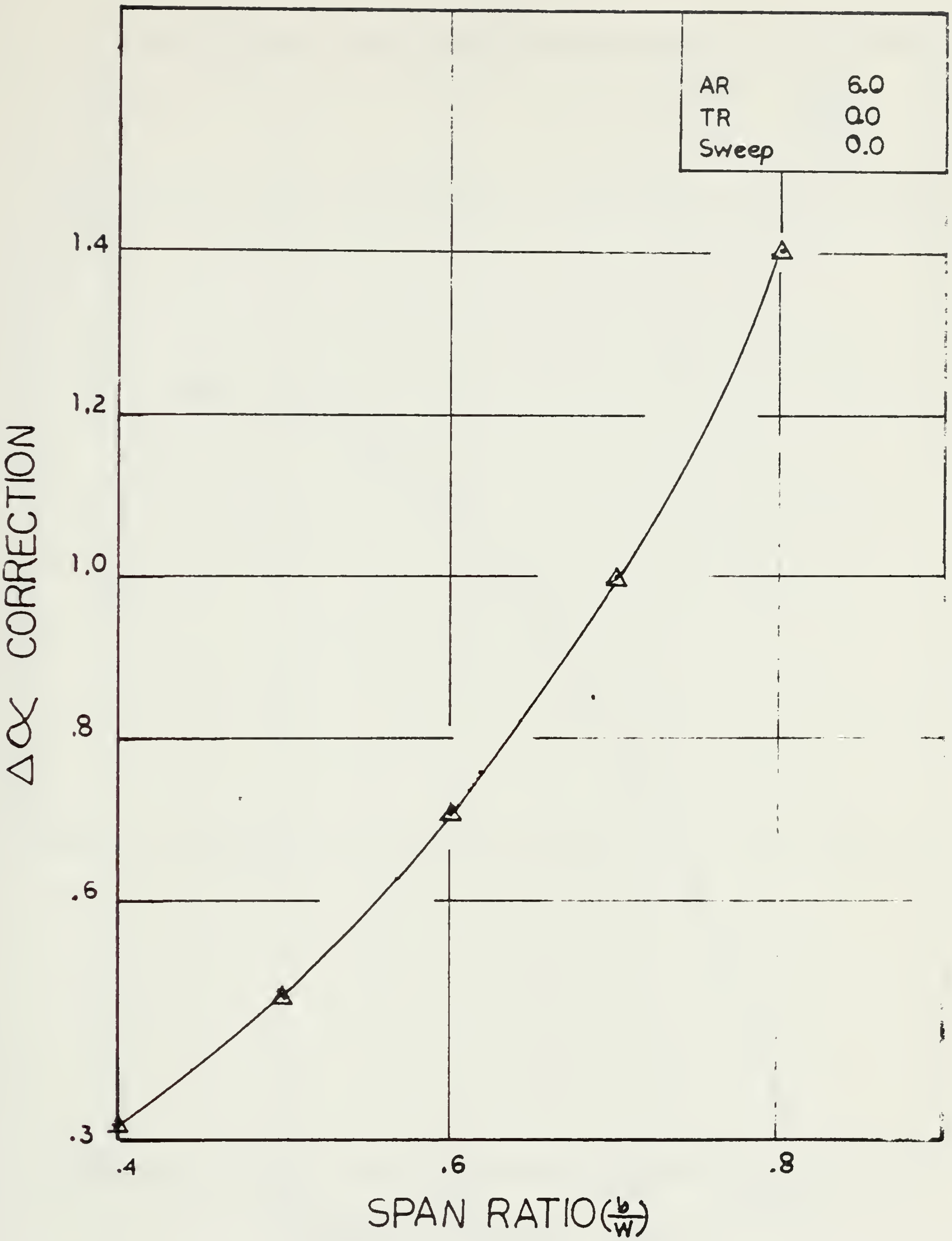

Figure 6. Angle of Attack Correction Factor Plotted as a Function of Span Ratio

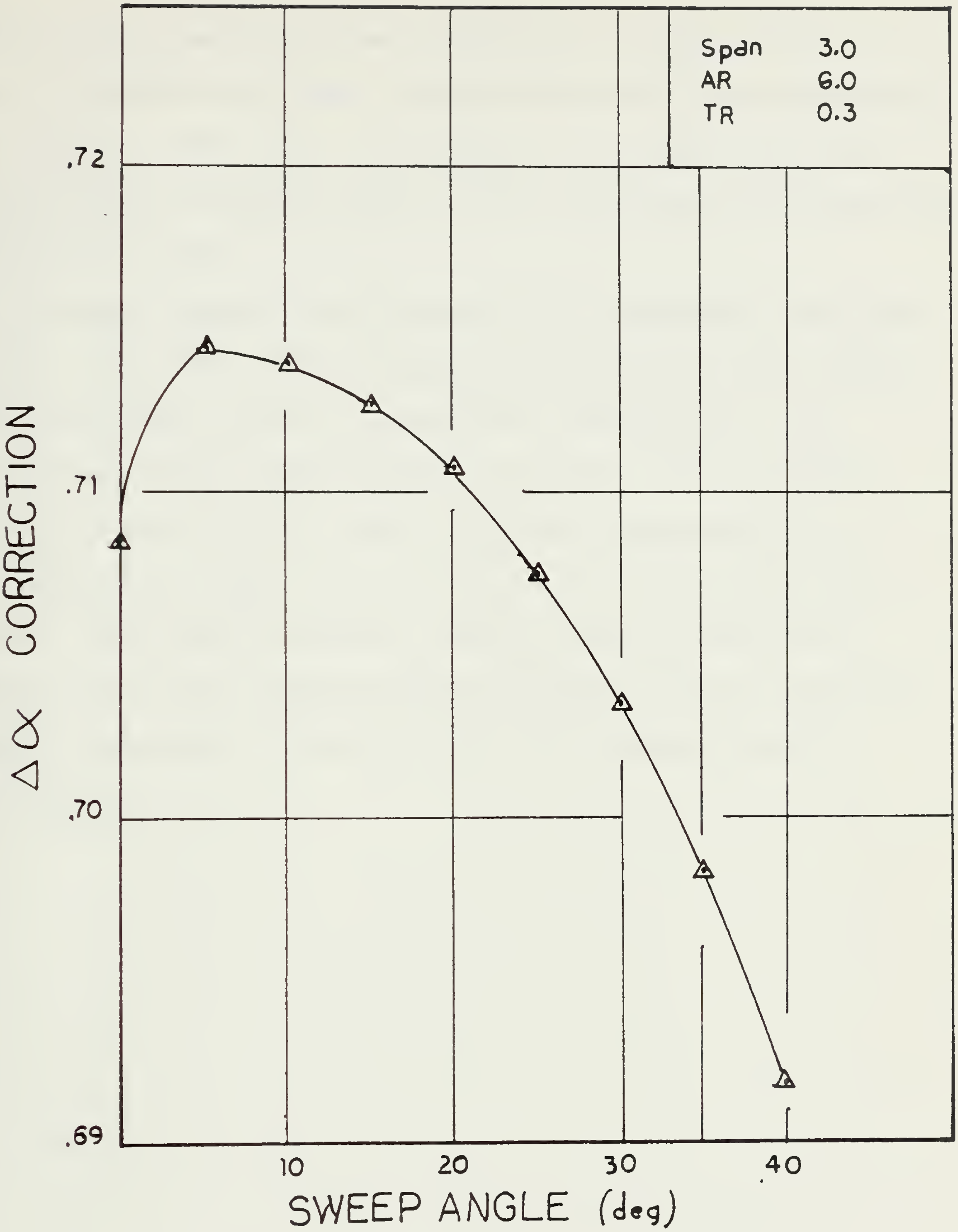

Figure 7. Angle of Attack Correction Factor Plotted As A Function Of Sweep Angle

which spans the wind tunnel represents an approximation to the two-dimensional wing. Induced drag for a two-dimensional wing should equal zero. In addition, the wind-tunnel lift curve slope is within 0.0006 of the theoretical two-dimensional value of 2π rad^{-1}.

A sample computer run was made for the moment correction factor. The tail quarter-chord was placed two feet behind the wing bound vortex, on the tunnel centerline. The correction factor obtained for a straight wing of aspect ratio 6.0 was -0.2297. For a wing with sweep angle of 30 degrees and taper of 0.3, a value of -0.1887 was calculated. The above correction factors must be multiplied by the stabilizer effectiveness parameter, using consistent angular measures, in order to find the pitching moment correction.

IV. CONCLUSIONS AND RECOMMENDATIONS

It is felt that the vortex lattice computer program as presented in this paper offers a very reliable and flexible tool for the determination of wind-tunnel wall corrections. It is capable of treating wings of any span, taper ratio, aspect ratio, and quarter-chord sweep, subject to the constraint of straight leading and trailing edges. The geometric shape of the wind tunnel cross-section can similarly be varied at the discretion of the program user. Resultant accuracy appears to be excellent. However, caution should be exercised in determining the vortex loop size. As the wing is positioned closer to the walls, a smaller, more definitive vortex loop representation must be used.

A logical extension of this program would be the inclusion of wings with an antisymmetric load distribution. Furthermore, slight modifications could incorporate the ability to consider the wall effects on other stability derivatives. In its present form, this program offers the wind tunnel user a versatile tool for determination of wind tunnel wall corrections.

APPENDIX A

The general assumptions used in the compilation of this program are listed below.

1. The two-dimensional lift-curve slope is 2π rad^{-1}.
2. The wing load distribution is symmetrical.
3. Aeroelastic effects were not considered.
4. The wing is located on the horizontal and vertical centerline of the wind tunnel.
5. The leading and trailing edges of the wing are straight.

APPENDIX B

DEVELOPMENT OF INDUCED VELOCITY EQUATIONS

The equations required to solve for induced velocities consist of two main types. One equation solves for the velocity induced by an arbitrarily oriented vortex segment, whereas the other basic equation applies to horseshoe vortex elements. These equations have been incorporated in subroutines LOOP and HSHOE, respectively. The development of these equations presented below follows closely that found in Ref. 4 and 5.

According to the Biot-Savart law, the velocity induced at a point p is found from:

$$\bar{w} = \frac{\Gamma}{4\pi h} (\cos B_1 + \cos B_2)\ \bar{v} \tag{1B}$$

For vortex segments oriented in the Y-Z plane,

$$\cos B_1 + \cos B_2 = \frac{R_1 + R_2}{2R_1R_2S} (S^2 - (R_1 - R_2)^2) \tag{2B}$$

It is now necessary to consider $\bar{v}$, the unit vector which establishes direction. From Fig. 8, it can be seen that

$$\bar{v} = \frac{\bar{R}_1 \times \bar{S}}{|\bar{R}_1 \times \bar{S}|} \tag{3B}$$

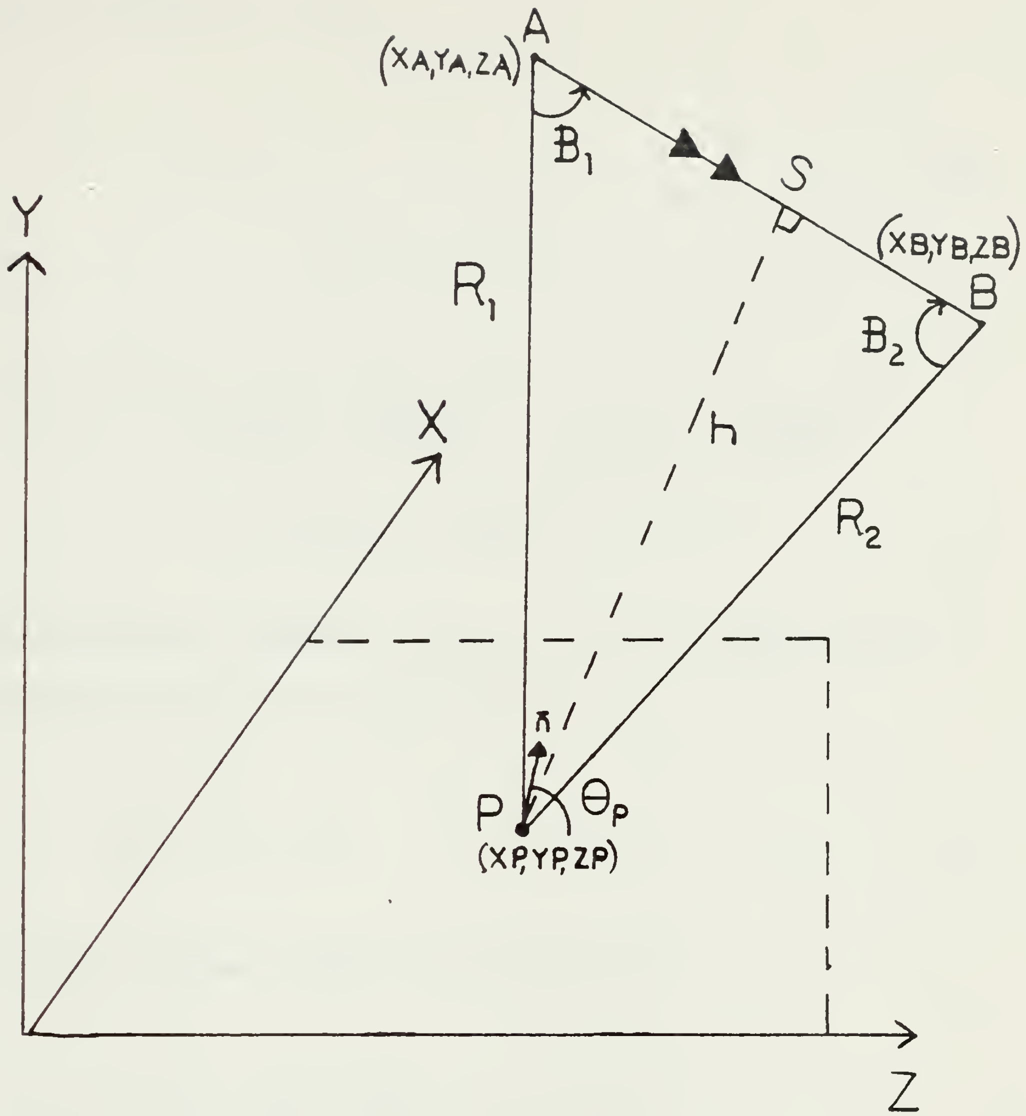

Figure 8. Velocity Induced By A Vortex Segment

Noting from Fig. 8 that

$$hs = |\overline{R}_1 \times \overline{S}| \tag{4B}$$

then

$$hs = [(R_{1y}S_z - R_{1z}S_y)^2 + (R_{1z}S_x - R_{1x}S_z)^2 + (R_{1x}S_y - R_{1y}S_x)^2]^{1/2}$$

Calculating the induced velocity in the direction of outward normal of point P per unit Γ,

$$\frac{w}{\Gamma} = \frac{\overline{v}}{\Gamma} \cdot \overline{n} \tag{5B}$$

where the unit normal vector is defined by:

$$\overline{n} = o\overline{i} + (\sin \theta p)\overline{j} + (\cos \theta p)\overline{k}$$

Therefore, one finally obtains:

$$\frac{w}{\Gamma} = \frac{R_1 + R_2}{8\pi R_1 R_2 (hs)^2} [S^2 - (R_1 - R_2)^2] \cdot [(\sin \theta p)(R_{1z}S_x - R_{1x}S_z) + (\cos \theta p)(R_{1x}S_y - R_{1y}S_x)] \tag{6B}$$

A conditional statement must be included in the program to set the downwash equal to zero if hs is equal to zero. This will preclude having a zero term in the denominator.

The trailing elements of a vortex loop can be treated with more simplicity. For these segments,

$$\cos B_1 = \frac{(R_1^{\,2} - h^2)^{1/2}}{R_1}$$

$$\cos B_2 = \frac{(R_2^{\,2} - h^2)^{1/2}}{R_2} \qquad (7B)$$

However, it can be seen from Fig. 8 that

$$R_1^{\,2} = (xp - xA)^2 + (yA - yp)^2 + (zA - zp)^2$$

$$h^2 = (yA - yp)^2 + (zA - zp)^2 \qquad (8B)$$

Combining equations 7 and 8,

$$\cos B_1 = \frac{xp - xA}{R_1}$$

$$\cos B_2 = \frac{xB - xp}{R_2} \qquad (9B)$$

As a result, the equation for the trailing elements of a vortex loop is simply

$$\frac{w}{\Gamma} = \frac{\cos B_1 + \cos B_2}{4\pi h^2} [(\sin \theta p)(zA - zp) + (\cos \theta p)(yp - yA)] \tag{10B}$$

For the horseshoe vortex, the equation for the bound segment is identical to equation 6. Similarly, the trailing elements can be treated as in equation 11 with a slight modification. In this case, the cosine of one enclosed angle is equal to 1, since the trailing element extends downstream to infinity. The induced velocity equation becomes

$$\frac{w}{\Gamma} = \frac{1 + \cos B_1}{4\pi h^2}[(zA - zp)\bar{j} + (yp - yA)\bar{k}]$$

$$\frac{w}{\Gamma} = \frac{1 + \cos B_1}{4\pi h^2}[(\sin \theta p)(zA - zp) + (\cos \theta p)(yp - yA)] \tag{11B}$$

APPENDIX C

COMPUTER PROGRAM INPUT

Card Number	Column Number	Description	Format
1	1-72	Program title	18A4
2	1-5	MM=Number of Spanwise Stations	I5
	6-10	NN=Number of Downstream Stations	I5
	11-20	Deltax=Loop length	F10.0
3	1	NOPT=1 for Ground Effect	I1
	2	NTAIL=1 for tail-on	I1
4	1-72	Tunnel y-coordinates (one quadrant only)	8F10.0
5	1-72	Tunnel z-coordinates (one quadrant only)	8F10.0
6	1-10	Span	F10.0
	11-20	Aspect Ratio	F10.0
	21-30	Taper Ratio	F10.0
	31-40	c/4 Sweep (degrees)	F10.0
7	1-10	x-Coordinate of tail quarter-chord	F10.0
	11-20	z-Coordinate of tail quarter-chord	F10.0

Input cards 5 and 6 can be repeated for different planforms and tail locations.

```
C*****************************************************************************
C   THIS PROGRAM IS DESIGNED TO CALCULATE THE INTERFERENCE PARAMETERS
C   FOR ARBITRARY PLANFORMS IN THE PRESENCE OF THE GROUND OR A WIND-
C   TUNNEL OF ANY CROSS-SECTIONAL SHAPE.CORRECTION FACTORS ARE COMPUTED
C   FOR ANGLE OF ATTACK,INDUCED DRAG,AND PITCHING MOMENT (FOR TAIL-
C   ON CONFIGURATIONS).
C*****************************************************************************
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/C1/  DELTAX,P8,P4,PI,MM,NN,N4
      COMMON/C2/  SPAN,AR,TR,SC4,B2,NS
      COMMON/C3/  XH(10),XWP(10),ZH1(10),ZH2(10),ZWP(10),C(10),ETA(12)
      COMMON/C4/  XL1(50),XL3(50),YL1(50),YL2(50),ZL1(50),ZL2(50)
      COMMON/C5/  YLP(50),XLP(50),ZLP(50),THETAP(50),X(10),Y(10),Z(10)
      DIMENSION   ROL(50,50),WOL(50,10),ROW(10,50)
      DIMENSION   GAMAL(50,10),W(10,10),CLC2(12),CDC2(12)
      DIMENSION   DAERO(10,10),WD(10,10),CLC(10),CDC(10)
      DIMENSION   TITLE(20),AERO(10,10),COORD(20)
      DIMENSION   ROT(1,50),WOT(1,10),WT(1,10),CLCFA(10),CLCT(10)
C
C
 1001 FORMAT(18A4)
 1002 FORMAT(4F10.0)
 1003 FORMAT(2I5,F10.0)
 1004 FORMAT(8F10.0)
 1005 FORMAT(2I1)
 1006 FORMAT(2F10.0)
 2001 FORMAT(1H1,18A4//)
 2002 FORMAT(' ',T12,5HMM = ,I2,1X,41HVORTEX RECTANGLES IN TUNNEL CIRCUM
     2FERENCE/T12,5HNN = ,I2,1X,28HVORTEX RECTANGLES DOWNSTREAM/
     2T8,9HDELTAX = ,F3.1,1X,37HFEET(RECTANGLE LENGTH IN X-DIRECTION)//)
 2003 FORMAT(' ',T5,19HFREE-AIR SPAN LOADS//)
 2004 FORMAT(' ',T7,3HETA,T20,3HL/Q,T34,3HD/Q/)
 2005 FORMAT(' ',T5,F7.4,T18,F9.6,T32,F9.6)
 2006 FORMAT(//1X,T5,32HTHE FREE-AIR LIFT CURVE SLOPE = ,F6.4,1X,
     210HPER RADIAN/T5,32HTHE FREE-AIR INDUCED DRAG      = ,F6.4///)
 2007 FORMAT(' ',T5,22HWIND-TUNNEL SPAN LOADS//)
 2008 FORMAT(//1X,T7,35HTHE WIND-TUNNEL LIFT CURVE SLOPE = ,F6.4,
     21X,10HPER RADIAN/T7,35HTHE WIND-TUNNEL INDUCED DRAG      = ,F6.4//)
 2009 FORMAT(' ',T5,28HWIND-TUNNEL WALL CORRECTIONS//T7,12HDEL-ALPHA = ,
     2F7.5,1X,8HCL (DEG)/T7,12HDEL-CD     = ,F7.5,1X,5HCL**2//)
 2010 FORMAT(' ',T5,24HGROUND EFFECT SPAN LOADS//)
 2011 FORMAT(' ',T7,37HTHE GROUND-EFFECT LIFT CURVE SLOPE = ,F6.4,
     21X,10HPER RADIAN/T7,37HTHE GROUND-EFFECT INDUCED DRAG      = F6.4/)
 2012 FORMAT(//1X,T7,35HTHE WING HEIGHT ABOVE THE GROUND = ,F5.2,
     21X,4HFEET/)
 2013 FORMAT(' ',T7,26HTHE GROUND EFFECT RATIO = ,F6.4/)
 2014 FORMAT(' ',T10,7HSPAN = ,F3.1,1X,4HFEET/T2,15HASPECT RATIO = ,
     2F3.1/T3,14HTAPER RATIO = ,F3.1/T5,12HC/4 SWEEP = ,F3.0,1X,
```

```
     27HDEGREES/T12,5HNS =  ,I2,1X,24HHORSESHOES PER SEMI-SPAN//)
 2015 FORMAT(' ',T7,12HDEL-CM    = ,F7.5,1X,10HPER RADIAN,1X,
     24CHTIMES STABILIZER EFFECTIVENESS PARAMETER)
 2016 FORMAT(//1X,T7,20HTHE TAIL POSITION = ,F6.3,1X,
     217HFEET(X-DIRECTION)/T7,20HTHE TAIL POSITION = F6.3,1X,
     217HFEET(Z-DIRECTION)//)
C
C
      READ(5,1001) (TITLE(I),I=1,18)
C    READ TUNNEL PARAMETERS.
C
C           NOPT=0 : CALCULATIONS ARE FOR WIND TUNNEL.
C           NOPT=1 : CALCULATIONS ARE FOR GROUND EFFECT.
C          NTAIL=1 : CALCULATIONS ARE MADE FOR TAIL-ON CONFIGURATION.
      READ(5,1005) NOPT,NTAIL
      READ(5,1003) MM,NN,DELTAX
           M4=MM/4
      IF (NOPT.EQ.1) M4=MM/2
           NNM4=NN*M4
           NNEW=NNM4-M4+1
            M41=M4+1
C   READ IN WALL COORDINATES
      READ(5,1004) (Y(I),I=1,M41)
      READ(5,1004) (Z(I),I=1,M41)
      PI=3.14159270O
      P4=4.0D0*3.14159264D0
            P8=8.0D0*PI
C
C
C
      CALL GEOMT
C    CALCULATION OF WALL EFFECT ON WALL CONTROL PTS.
C    ESTABLISH COORD FOR THIS CONTROL PT.
       DO 160 I=1,NNM4
       COORD(1)=XLP(I)
       COORD(2)=YLP(I)
       COORD(3)=ZLP(I)
       COORD(4)=THETAP(I)*57.2957795D0
C    ESTABLISH COORD FOR LOOPS
       DO 140 J=1,NNM4
          WASH3=0.0D0
          WASH4=0.0D0
            HL3=0.0D0
            HL4=0.0D0
      IF (J.GE.NNEW) GO TO 135
       COORD(5)=XL1(J)
       COORD(6)=XL3(J)
       COORD(7)=YL1(J)
```

```
      COORD(8)=YL2(J)
      COORD(9)=ZL1(J)
     COORD(10)=ZL2(J)
C   CALCULATE EFFECT IN QUADRANT 1
       CALL LOCP (COORD,WASH1)
C   ESTABLISH COORD FOR QUADRANT 2
      COORD(7)=YL2(J)
      COORD(8)=YL1(J)
      COORD(9)=-ZL2(J)
     COORD(10)=-ZL1(J)
C
C   CALCULATE EFFECT IN QUADRANT 2
       CALL LOCP(COORD,WASH2)
     IF (NOPT.EQ.1) GO TO 134
C   ESTABLISH COORD FOR QUADRANT 3
      COORD(7)=-YL2(J)
      COORD(8)=-YL1(J)
      COORD(9)=-ZL2(J)
     COORD(10)=-ZL1(J)
C   CALCULATE EFFECT IN QUADRANT 3
       CALL LOCP(COORD,WASH3)
C   ESTABLISH COORD FOR QUADRANT 4
      COORD(7)=-YL1(J)
      COORD(8)=-YL2(J)
      COORD(9)=ZL1(J)
     COORD(10)=ZL2(J)
C   CALCULATE EFFECT IN QUADRANT 4
       CALL LOCP(COORD,WASH4)
  134 CONTINUE
      RCL(I,J)=WASH1+WASH2+WASH3+WASH4
      GO TO 139
  135 CONTINUE
C  CALCULATE EFFECT FROM END HORSESHOES
C   ESTABLISH COORD FOR QUADRANT 1
      COORD(5)=XL1(J)
      COORD(6)=YL1(J)
      COORD(7)=YL2(J)
      COORD(8)=ZL1(J)
      COORD(9)=ZL2(J)
C   CALCULATE EFFECT FOR QUADRANT 1
       CALL HSHOE (COORD,HL1)
C   ESTABLISH COORD FOR QUADRANT 2
      COORD(6)=YL2(J)
      COORD(7)=YL1(J)
     COORD(8)=-ZL2(J)
      COORD(9)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 2
       CALL HSHOE (COORD,HL2)
```

```
      IF (NOPT.EQ.1) GO TO 138
C   ESTABLISH COORD FOR QUADRANT 3
      COORD(6)=-YL2(J)
      COORD(7)=-YL1(J)
      COORD(8)=-ZL2(J)
      COORD(9)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 3
      CALL HSHOE (COORD,HL3)
C   ESTABLISH COORD FOR QUADRANT 4
      COORD(6)=-YL1(J)
      COORD(7)=-YL2(J)
      COORD(8)=ZL1(J)
      COORD(9)=ZL2(J)
C   CALCULATE EFFECT FROM QUADRANT 4
      CALL HSHOE (COORD,HL4)
  138 CONTINUE
      RCL(I,J)=HL1+HL2+HL3+HL4
  139 CONTINUE
  140 CONTINUE
  160 CONTINUE
C
C
C
C  INVERT THE WALL INFLUENCE COEFFICIENT MATRIX.
      CALL INVR (ROL,NNM4,50)
C
C
C
  165 CONTINUE
C  READ IN NEW WING PARAMETERS FOR THIS COMPUTATION.
      READ(5,1002) SPAN,AR,TR,SC4
C  IF THERE IS NO MORE WING PARAMETER INPUT,GO TO END
C  OF PROGRAM.
      IF (SPAN.EQ.0.0D0) GO TO 500
C  ENTER THE NUMBER OF WING HORSESHOE VORTICES.
C  NS = NO. OF HORSESHOE VORTICES (ONE SIDE ONLY)
      NS=10
      WRITE(6,2001) (TITLE(I),I=1,18)
C   WRITE TUNNEL PARAMETERS.
      WRITE(6,2002) MM,NN,DELTAX
C   WRITE WING PARAMETERS.
      WRITE(6,2014) SPAN,AR,TR,SC4,NS
      CALL GEOMW
C
C
C
C  CALCULATE EFFECT OF WING ON WALL CONTROL PTS.
C   ESTABLISH COORD FOR WALL CONTROL PTS.
```

```
          DO 190I =1,NNM4
          COORD(1)=XLP(I)
          COORD(2)=YLP(I)
          COORD(3)=ZLP(I)
          COORD(4)=THETAP(I)*57.2957795D0
C      ESTABLISH COORD FOR LEFT WING
          DO 170 J=1,NS
          COORD(5)=XH(J)
          COORD(6)=0.0D0
          COORD(7)=0.0D0
          COORD(8)=ZH1(J)
          COORD(9)=ZH2(J)
C      CALCULATE EFFECT FROM LEFT WING
            CALL HSHOE(COORD,WASHL)
C
C      ESTABLISH COORD FOR RT. WING
          COORD(8)=-ZH2(J)
          COORD(9)=-ZH1(J)
C      CALCULATE EFFECT FROM RT. WING
            CALL HSHOE(COORD,WASHR)
          WOL(I,J)=WASHL+WASHR
  170 CONTINUE
  190 CONTINUE
C      SOLVE THE MATRIX EQN: (ROL)*(GAMAL)=-(WOL)*(GAMAW)
          DO 195I = 1,NNM4
          DO 194J = 1,NS
               WW=0.0D0
          DO 193K = 1,NNM4
               WW=WW+ROL(I,K)*WOL(K,J)
  193 CONTINUE
        GAMAL(I,J)=WW
  194 CONTINUE
  195 CONTINUE
C
C
C
C     CALCULATE THE EFFECT OF WALL ON WING CONTROL PTS.
C      ESTABLISH COORD FOR WING CONTROL PTS.
          DO 220I =1,NS
          COORD(1)=XWP(I)
          COORD(2)=0.0D0
          COORD(3)=ZWP(I)
          COORD(4)=-90.0D0
C      ESTABLISH COORD FOR LOOP
          DO 210J = 1,NNM4
             WASH3=0.0D0
             WASH4=0.0D0
               HL3=0.0D0
```

```
      HL4=0.0D0
   IF (J.GE.NNEW) GO TO 208
    COORD(5)=XL1(J)
    COORD(6)=XL3(J)
    COORD(7)=YL1(J)
    COORD(8)=YL2(J)
    COORD(9)=ZL1(J)
   COORD(10)=ZL2(J)
C   CALCULATE EFFECT FROM QUADRANT 1
     CALL LOOP (COORD,WASH1)
C   ESTABLISH COORD FOR QUADRANT 2
    COORD(7)=YL2(J)
    COORD(8)=YL1(J)
    COORD(9)=-ZL2(J)
   COORD(10)=-ZL1(J)
C   CALCULATE EFFECT FOR QUADRANT 2
    CALL LOOP (COORD,WASH2)
   IF (NOPT.EQ.1) GO TO 207
C   ESTABLISH COORD FOR QUADRANT 3
    COORD(7)=-YL2(J)
    COORD(8)=-YL1(J)
    COORD(9)=-ZL2(J)
   COORD(10)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 3
     CALL LOOP (COORD,WASH3)
C   ESTABLISH COORD FOR QUADRANT 4
   COORD(7)=-YL1(J)
   COORD(8)=-YL2(J)
    COORD(9)=ZL1(J)
   COORD(10)=ZL2(J)
C   CALCULATE EFFECT FROM QUADRANT 4
     CALL LOOP (COORD,WASH4)
  207 CONTINUE
C   ADD CONTRIBUTIONS FROM EACH QUADRANT
    ROW(I,J)=WASH1+WASH2+WASH3+WASH4
    GO TO 209
  208 CONTINUE
C  CALCULATE EFFECT FROM END HORSESHOES
C   SET COORD FOR END HORSESHOES
C   CALCULATIONS FOR QUADRANT 1
    COORD(5)=XL1(J)
    COORD(6)=YL1(J)
    COORD(7)=YL2(J)
    COORD(8)=ZL1(J)
    COORD(9)=ZL2(J)
C   CALCULATE EFFECT FOR QUADRANT 1
     CALL HSHOE (COORD,HL1)
C   ESTABLISH COORD FOR QUADRANT 2
```

```
         COORD(6)=YL2(J)
         COORD(7)=YL1(J)
        COORD(8)=-ZL2(J)
         COORD(9)=-ZL1(J)
C    CALCULATE EFFECT FROM QUADRANT 2
          CALL HSHOE (COORD,HL2)
        IF (NOPT.EQ.1) GO TO 206
C    ESTABLISH COORD FOR QUADRANT 3
         COORD(6)=-YL2(J)
         COORD(7)=-YL1(J)
         COORD(8)=-ZL2(J)
         COORD(9)=-ZL1(J)
C    CALCULATE EFFECT FROM QUADRANT 3
          CALL HSHOE (COORD,HL3)
C    ESTABLISH COORD FOR QUADRANT 4
         COORD(6)=-YL1(J)
         COORD(7)=-YL2(J)
         COORD(8)=ZL1(J)
         COORD(9)=ZL2(J)
C    CALCULATE EFFECT FROM QUADRANT 4
          CALL HSHOE (COORD,HL4)
  206 CONTINUE
         RCW(I,J)=HL1+HL2+HL3+HL4
  209 CONTINUE
  210 CONTINUE
  220 CONTINUE
C
C
C
C   CALCULATE THE DOWNWASH PRODUCED BY THE WING HORSESHOES
C   ON THE WING CONTROL PTS. (AERO).
        DO 40 I=1,NS
C   DEFINE CONTROL PT. COORDINATES FOR THIS ITERATION
        COORD(1)=XWP(I)
        COORD(2)=0.0D0
        COORD(3)=ZWP(I)
        COORD(4)=-90.0D0
        DO 30 J=1,NS
C   ESTABLISH COORD FOR LEFT SIDE OF WING
        COORD(5)=XH(J)
        COORD(6)=0.0D0
        COORD(7)=0.0D0
        COORD(8)=ZH1(J)
        COORD(9)=ZH2(J)
C   CALCULATE DOWNWASH FROM LEFT SIDE OF WING
        CALL HSHOE (COORD,WSHL)
C   ESTABLISH COORD FOR RIGHT SIDE OF WING
        COORD(8)=-ZH2(J)
```

```
      COORD(9)=-ZH1(J)
C   CALCULATE DOWNWASH FROM RIGHT SIDE OF WING
      CALL HSHOE (COORD,WSHR)
      AERO(I,J)=(WSHL+WSHR)*0.5D0
30    CONTINUE
40    CONTINUE
C
C
C   ESTABLISH COORD FOR INDUCED DRAG CALCULATION
      DO 60 I=1,NS
C   DEFINE C/4 CONTROL POINTS FOR THIS ITERATION
      COORD(1)=XH(I)
      COORD(2)=0.0D0
      COORD(3)=ZWP(I)
      COORD(4)=-90.0D0
C   ESTABLISH COORD FOR LEFT WING
      DO 50 J=1,NS
      COORD(5)=XH(J)
      COORD(6)=0.0D0
      COORD(7)=0.0D0
      COORD(8)=ZH1(J)
      COORD(9)=ZH2(J)
C   CALCULATE C/4 DOWNWASH FOR LEFT WING
      CALL HSHOE (COORD,WSHL)
C   ESTABLISH COORD FOR RIGHT WING
      COORD(8)=-ZH2(J)
      COORD(9)=-ZH1(J)
C   CALCULATE C/4 DOWNWASH FOR RIGHT WING
      CALL HSHOE (COORD,WSHR)
      AERO(I,J)=(WSHL+WSHR)*0.5D0
50    CONTINUE
60    CONTINUE
C
C
C
C   FIND THE TOTAL DOWNWASH AT WING CONTROL PTS.
C    MULTIPLY (ROW)*(GAMAL) TO GET WALL EFFECT ON WING CONTROL PTS.
        DO 250I = 1,NS
C   SET 1.0 RADIAN ANGLE OF ATTACK ACROSS SEMI-SPAN.
          CLC(I)=1.0D0
        DO 240J = 1,NS
              WW=0.0D0
        DO 230K = 1,NNM4
        WW=WW+ROW(I,K)*GAMAL(K,J)
  230 CONTINUE
C   SET (W) EQUAL TO TOTAL WING DOWNWASH (AERO-WALL EFFECT)
          W(I,J)=(AERO(I,J)-(WW*0.5D0))
  240 CONTINUE
```

```
  250 CONTINUE
C
C  ELU AND SLVB TO SOLVE   :(L/Q)*(AERO)=(ALPHA)
      CALL ELU (AERO,NS,10)
      CALL SLVB (AERO,NS,10,CLC)
      WRITE(6,2003)
      WRITE(6,2004)
C
C  SOLVE THE MATRIX EQN : (D/Q)=(L/Q)*(DAERO)*(L/Q)
      DO 80 I=1,NS
      D1=0.0D0
      DO 90 K=1,NS
      D1 = D1+DAERO(I,K)*CLC(K)
90    CONTINUE
C  OBTAIN CDC
      CDC(I) = CLC(I)*D1
           ETA2=ZWP(I)/B2
C  WRITE WING SPAN LOADS IN FREE AIR.
      WRITE(6,2005) ETA2,CLC(I),CDC(I)
80    CONTINUE
        CLC2(1)=CLC(1)
       CLC2(12)=0.0D0
       CDC2(1)=CDC(1)
        CDC2(12)=0.0D0
        DO 101I =2,11
       CDC2(I)=CDC(I-1)
       CLC2(I) =CLC(I-1)
      CLCFA(I-1)=CLC(I-1)
  101 CONTINUE
C
C   INTEGRATE SPAN LOADS TO OBTAIN LIFT-CURVE SLOPE
C   AND INDUCED DRAG IN FREE AIR.
        CALL DQTFG (ETA,CLC2,CLC2,12)
       CALL DQTFG (ETA,CDC2,CDC2,12)
           CAVE=SPAN/AR
           CLFA=CLC2(NS+2)/CAVE
           CDFA=CDC2(NS+2)/CAVE
      WRITE(6,2006) CLFA,CDFA
C
C
C
C  CALCULATE WALL EFFECT ON WING C/4 CONTROL PTS FOR
C  INDUCED DRAG CALCULATIONS.
C   ESTABLISH COORD FOR WING C/4 PTS.
       DO 280I = 1,NS
       COORD(1)=XH(I)
       COORD(2)=0.0D0
       COORD(3)=ZWP(I)
```

```
      COORD(4)=-90.0D0
      DO 270J = 1,NNM4
         WASH3=0.0D0
         WASH4=0.0D0
           HL3=0.0D0
           HL4=0.0D0
     IF (J.GE.NNEW) GO TO 265
C   CALCULATIONS FOR QUADRANT 1
      COORD(5)=XL1(J)
      COORD(6)=XL3(J)
      COORD(7)=YL1(J)
      COORD(8)=YL2(J)
      COORD(9)=ZL1(J)
     COORD(10)=ZL2(J)
C   CALCULATE EFFECT FROM QUADRANT 1
       CALL LOOP (COORD,WASH1)
C   ESTABLISH COORD FOR QUADRANT 2
      COORD(7)=YL2(J)
      COORD(8)=YL1(J)
      COORD(9)=-ZL2(J)
     COORD(10)=-ZL1(J)
C   CALCULATE EFFECT FOR QUADRANT 2
      CALL LOOP (COORD,WASH2)
     IF (NOPT.EQ.1) GO TO 264
C   ESTABLISH COORD FOR QUADRANT 3
      COORD(7)=-YL2(J)
      COORD(8)=-YL1(J)
      COORD(9)=-ZL2(J)
     COORD(10)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 3
       CALL LOOP (COORD,WASH3)
C   ESTABLISH COORD FOR QUADRANT 4
     COORD(7)=-YL1(J)
     COORD(8)=-YL2(J)
      COORD(9)=ZL1(J)
     COORD(10)=ZL2(J)
C   CALCULATE EFFECT FROM QUADRANT 4
       CALL LOOP (COORD,WASH4)
  264 CONTINUE
C   ADD CONTRIBUTIONS FROM EACH QUADRANT
      RCW(I,J)=WASH1+WASH2+WASH3+WASH4
      GO TO 269
  265 CONTINUE
C   SET COORD FOR END HORSESHOES
      COORD(5)=XL1(J)
      COORD(6)=YL1(J)
      COORD(7)=YL2(J)
      COORD(8)=ZL1(J)
```

```
      CCCRC(9)=ZL2(J)
C   CALCULATE EFFECT FOR QUADRANT 1
        CALL HSHOE (COORD,HL1)
C   ESTABLISH COORD FOR QUADRANT 2
      CCCRC(6)=YL2(J)
      COORC(7)=YL1(J)
     CCCRD(8)=-ZL2(J)
      CCCRC(9)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 2
        CALL HSHOE (COORD,HL2)
     IF (NOPT.EQ.1) GO TO 268
C   ESTABLISH CCORD FOR QUADRANT 3
      COORC(6)=-YL2(J)
      CCCRD(7)=-YL1(J)
      CCORD(8)=-ZL2(J)
      CCORD(9)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 3
        CALL HSHOE (COORD,HL3)
C   ESTABLISH COORD FOR QUADRANT 4
      CCCRD(6)=-YL1(J)
      CCCRD(7)=-YL2(J)
      CCCRC(8)=ZL1(J)
      CCCRC(9)=ZL2(J)
C   CALCULATE EFFECT FROM QUADRANT 4
        CALL HSHCE (COORC,HL4)
  268 CCNTINUE
      RCW(I,J)=HL1+HL2+HL3+HL4
  269 CCNTINUE
  270 CCNTINUE
  280 CCNTINUE
C    (ROW)*(GAMAL) TO GET WALL EFFECT CN WING
C  C/4 CCNTROL PTS.
      CC 320I =1,NS
      CC 310J =1,NS
           WW =0.0D0
      CC 300K =1,NNM4
            WW=WW+ROW(I,K)*GAMAL(K,J)
  3CC CCNTINUE
C
C
C   SET (WD) EQUAL TO TOTAL DCWNWASH AT C/4 PTS : (DAERC-WALL EFFECT)
        WC(I,J)=(CAERO(I,J)-(WW*.5D0))
  31C CCNTINUE
     CLC(I)=1.0D0
  32C CCNTINUE
C
C   ELU AND SLVB TO SOLVE THE MATRIX EQUATION :
C    (ALPHA)=(AERC-W)*(L/Q).
```

```
      CALL ELU (W,NS,10)
      CALL SLVB (W,NS,10,CLC)
      IF(NOPT.EQ.1) GO TO 321
      WRITE(6,2007)
      GO TO 322
  321 CONTINUE
      WRITE(6,2010)
  322 CONTINUE
      WRITE(6,2004)
C
C   SOLVE THE MATRIX EQN. :(D/Q)=(L/Q)*(WD)*(L/Q)
      DO 330 I=1,NS
            D1=0.0D0
      DO 329 K=1,NS
            D1=D1+WD(I,K)*CLC(K)
  329 CONTINUE
C  OBTAIN CDC
        CDC(I)=CLC(I)*D1
          ETA2=ZWP(I)/B2
C  WRITE WING SPAN LOADS IN PRESENCE OF WALL.
      WRITE(6,2005) ETA2,CLC(I),CDC(I)
  330 CONTINUE
       CLC2(1)=CLC(1)
       CDC2(1)=CDC(1)
      CLC2(12)=0.0D0
      CDC2(12)=0.0D0
      DO 340 I=2,11
       CLC2(I)=CLC(I-1)
       CDC2(I)=CDC(I-1)
      CLCT(I-1)=CLC(I-1)
  340 CONTINUE
C   INTEGRATE SPAN LOADS TO OBTAIN LIFT-CURVE SLOPE
C   AND INDUCED DRAG IN WALL EFFECT.
      CALL DQTFG (ETA,CLC2,CLC2,12)
      CALL DQTFG (ETA,CDC2,CDC2,12)
           CLT=CLC2(NS+2)/CAVE
           CDT=CDC2(NS+2)/CAVE
      IF(NOPT.EQ.1) GO TO 342
      WRITE(6,2008) CLT,CDT
           DKT=CDT/(CLT**2)
          DKFA=CDFA/(CLFA**2)
         DELCD=DKFA-DKT
C  CONVERT LIFT-CURVE SLOPE TO DEGREES.
          CLFA=CLFA*.0174532900
           CLT=CLT*.0174532900
          DELA=(1.0D0/CLFA-1.0D0/CLT)
      WRITE(6,2009) DELA,DELCD
      GO TO 341
```

```
  342 CONTINUE
C  WRITE WING HEIGHT ABOVE THE GROUND.
      WRITE(6,2012) Y(1)
      WRITE(6,2011) CLT,CDT
C   CALCULATE THE GROUND-EFFECT RATIO.
            GER= CLT/CLFA
      WRITE(6,2013) GER
  341 CONTINUE
C  GO TO THE END OF PROGRAM FOR TAIL-OFF CONFIGURATIONS.
      IF (NTAIL.NE.1) GO TO 400
C
C
C
C  READ IN X AND Z COORDINATES OF TAIL QUARTER-CHORD.
      READ(5,1006) XT,ZT
      WRITE(6,2016) XT,ZT
C  CALCULATE DOWNWASH PRODUCED BY THE WING ON THE TAIL.
C   ESTABLISH COORD FOR TAIL POSITION.
       COORD(1)=XT
       COORD(2)=0.0D0
       COORD(3)=ZT
       COORD(4)=-90.0D0
C   ESTABLISH COORD FOR LEFT WING.
       DO 350 J=1,NS
       COORD(5)=XH(J)
       COORD(6)=0.0D0
       COORD(7)=0.0D0
       COORD(8)=ZH1(J)
       COORD(9)=ZH2(J)
C   CALCULATE EFFECT FROM LEFT WING
        CALL HSHOE (COORD,WASHL)
C
C   ESTABLISH COORD FOR RT. WING.
       COORD(8)=-ZH2(J)
       COORD(9)=-ZH1(J)
C   CALCULATE EFFECT FROM RT. WING.
        CALL HSHOE (COORD,WASHR)
      WOT(1,J)=(WASHL+WASHR)*0.5D0
  350 CONTINUE
C
C
C
C  CALCULATE EFFECT OF WALL ON TAIL.
C   ESTABLISH COORD FOR LOOP
C   ESTABLISH COORD FOR QUADRANT 1
       DO 370 J=1,NNM4
          WASH3=0.0D0
          WASH4=0.0D0
```

```
            HL3=0.0D0
            HL4=0.0D0
         IF(J.GE.NNEW) GO TO 360
         COORD(5)=XL1(J)
         COORD(6)=XL3(J)
         COORD(7)=YL1(J)
         COORD(8)=YL2(J)
         COORD(9)=ZL1(J)
        COORD(10)=ZL2(J)
C     CALCULATE EFFECT FROM QUADRANT 1
          CALL LOOP (COORD,WASH1)
C     ESTABLISH COORD FOR QUADRANT 2
         COORD(7)=YL2(J)
         COORD(8)=YL1(J)
         COORD(9)=-ZL2(J)
        COORD(10)=-ZL1(J)
C     CALCULATE EFFECT FROM QUADRANT 2
          CALL LOOP (COORD,WASH2)
C     SKIF QUADRANT 3 AND 4 FOR GROUND EFFECT CALCULATIONS.
        IF (NOPT.EQ.1) GO TO 359
C     ESTABLISH COORD FOR QUADRANT 3
         COORD(7)=-YL2(J)
         COORD(8)=-YL1(J)
         COORD(9)=-ZL2(J)
        COORD(10)=-ZL1(J)
C     CALCULATE EFFECT FROM QUADRANT 3
          CALL LOOP (COORD,WASH3)
C     ESTABLISH COORD FOR QUADRANT 4
         COORD(7)=-YL1(J)
         COORD(8)=-YL2(J)
         COORD(9)=ZL1(J)
        COORD(10)=ZL2(J)
          CALL LOOP (COORD,WASH4)
  359 CONTINUE
        ROT(1,J)=WASH1+WASH2+WASH3+WASH4
  360 CONTINUE
C     CALCULATE EFFECT FROM END HORSESHOES.
C     ESTABLISH COORD FOR QUADRANT 1
         COORD(5)=XL1(J)
         COORD(6)=YL1(J)
         COORD(7)=YL2(J)
         COORD(8)=ZL1(J)
         COORD(9)=ZL2(J)
C     CALCULATE EFFECT FROM QUADRANT 1
          CALL HSHOE (COORD,HL1)
C     ESTABLISH COORD FOR QUADRANT 2
         COORD(6)=YL2(J)
         COORD(7)=YL1(J)
```

```
      COORD(8)=-ZL2(J)
      COORD(9)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 2
        CALL HSHOE (COORD,HL2)
      IF (NOPT.EQ.1) GO TO 369
C   ESTABLISH COORD FOR QUADRANT 3
      COORD(6)=-YL2(J)
      COORD(7)=-YL1(J)
      COORD(8)=-ZL2(J)
      COORD(9)=-ZL1(J)
C   CALCULATE EFFECT FROM QUADRANT 3
        CALL HSHOE (COORD,HL3)
C   ESTABLISH COORD FOR QUADRANT 4
      COORD(6)=-YL1(J)
      COORD(7)=-YL2(J)
      COORD(8)=ZL1(J)
      COORD(9)=ZL2(J)
C   CALCULATE EFFECT FROM QUADRANT 4
        CALL HSHOE (COORD,HL4)
  369 CONTINUE
      ROT(1,J)=HL1+HL2+HL3+HL4
  370 CONTINUE
C  CALCULATE TAIL DOWNWASH ANGLE IN FREE AIR.
           EFA=0.0D0
      DO 380 I=1,NS
           EFA=EFA+WOT(1,I)*CLCFA(I)
  380 CONTINUE
C  CALCULATE TAIL DOWNWASH ANGLE IN THE PRESENCE OF THE WALL.
C   MULTIPLY (ROT)*(GAMAL) TO GET WALL EFFECT ON TAIL POSITION.
      DO 390 I=1,NS
           WWT=0.0D0
      DO 385 J=1,NAM4
           WWT=WWT+ROT(1,J)*GAMAL(J,I)
  385 CONTINUE
C   SET (WT) EQUAL TO TOTAL DOWNWASH AT THE TAIL.
        WT(1,I)=(WOT(1,I)-(WWT*0.5D0))
  390 CONTINUE
C   CALCULATE TAIL DOWNWASH ANGLE IN THE PRESENCE OF THE WALL.
           EWT=0.0D0
      DO 395 I=1,NS
           EWT=EWT+WT(1,I)*CLCT(I)
  395 CONTINUE
          DELE=EWT-EFA
      WRITE(6,2015) DELE
  400 CONTINUE
C   RETURN TO MAIN BODY OF PROGRAM FOR CALCULATIONS
C   WITH A NEW WING CONFIGURATION.
      GO TO 165
```

```
  500 CONTINUE
      STOP
      END
C*************************************************************************
C   GEOMT... TUNNEL GEOMETRY
C   SUBROUTINE GEOMT ESTABLISHES VORTEX RECTANGLE AND CONTROL
C   POINT COORDINATES REQUIRED TO CALCULATE LOOP DOWNWASH.
C
C         DELTAX=VORTEX RECTANGLE LENGTH (X-DIR)
C           SIDE=VORTEX RECTANGLE WIDTH
C             NN=NUMBER OF VORTEX RECTANGLES IN TUNNEL LENGTH
C                 INCLUDING THE END HORSESHOE.
C             M4=1/4 OF THE VORTEX RECTANGLES COMPRISING
C                 WIND TUNNEL CIRCUMFERENCE.
C             M4=1/2 OF THE VORTEX RECTANGLES COMPRISING
C                 THE GROUND REPRESENTATION.
C
C                 M4 X NN SHOULD NOT EXCEED 50.
C*************************************************************************
      SUBROUTINE GEOMT
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/C1/  DELTAX,P8,P4,PI,MM,NN,M4
      COMMON/C4/  XL1(50),XL3(50),YL1(50),YL2(50),ZL1(50),ZL2(50)
      COMMON/C5/  YLP(50),XLP(50),ZLP(50),THETAP(50),X(10),Y(10),Z(10)
       DIMENSION SIDE(50)
         XN2=DFLOAT(NN/2)
        X(1)=-(XN2*DELTAX)
      DO 10I =2,NN
        X(I)=X(I-1)+DELTAX
   10 CONTINUE
           K=0
      DO 30 I= 1,NN
      DO 20 J=1,M4
           K=K+1
       XL1(K)=X(I)
       XL3(K)=XL1(K)+DELTAX
       XLP(K)=(XL1(K)+XL3(K))/2.0D0
       YL1(K)=Y(J)
       YL2(K)=Y(J+1)
       ZL1(K)=Z(J)
       ZL2(K)=Z(J+1)
        YLP(K)=(YL1(K)+YL2(K))/2.0D0
        ZLP(K)=(ZL1(K)+ZL2(K))/2.0D0
       SIDE(K)=DSQRT((YL2(K)-YL1(K))**2+(ZL2(K)-ZL1(K))**2)
      THETAP(K)=DARCOS((YL2(K)-YL1(K))/SIDE(K))
   20 CONTINUE
   30 CONTINUE
      RETURN
```

```
      END
C***********************************************************************
C   GEOMW... WING GEOMETRY
C   SUBROUTINE GEOMW COMPUTES PERTINENT WING GEOMETRY WHICH IS NEEDED TO
C   ESTABLISH THE AERODYNAMIC INFLUENCE COEFFICIENT MATRIX
C
C   SPAN = WING SPAN (FEET)
C     AR = ASPECT RATIO
C     TR = TAPER RATIO
C    SC4 = QUARTER CH'D SWEEP ANGLE (DEG)
C     NS = NO. OF EQUAL-WIDTH SEMI-SPAN STATIONS
C***********************************************************************
      SUBROUTINE GEOMW
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/C1/  DELTAX,P8,P4,PI,MM,NN,M4
      COMMON/C2/  SPAN,AR,TR,SC4,B2,NS
      COMMON/C3/  XH(10),XWP(10),ZH1(10),ZH2(10),ZWP(10),C(10),ETA(12)
           B2=SPAN/2.0D0
      ANS2=DFLOAT(NS)
      SWP= .0174533D0*SC4
      TC4=DTAN(SWP)
      BS=B2/ANS2
      CR=(2.0D0*SPAN)/((1.0D0+TR)*AR)
C   ASSUMPTION OF WING ON TUNNEL CNTR LINE
      YH1=0.0D0
      YH2=0.0D0
        ETA(12)=1.0D0
         ETA(1)=0.0D0
      DO 10 I=1,NS
      AI=DFLOAT(I)
      ZWP(I)=(AI-.5D0)*BS
       ETA(I+1)=ZWP(I)/B2
      ZH1(I)= AI*BS
      ZH2(I)= (AI-1.0D0)*BS
      C(I)= CR*(1.0D0+((TR-1.0D0)*ZWP(I)/B2))
      XH(I)= ZWP(I)*TC4
      XWP(I)=XH(I)+.5D0*C(I)
10    CONTINUE
      RETURN
      END
C***********************************************************************
C   SUBROUTINE HSHOE (COORD,WASH)
C   CALCULATES DOWNWASH VELOCITY DUE TO HORSESHOE VORTEX OF UNIT STRENGTH
C
C         COORD IS A 9 DIM COLUMN VECTOR
C   I=1: XP=X-COORD OF CONTROL POINT
C   I=2: YP=Y-COORD OF CONTROL POINT
C   I=3: ZP=Z-COORD OF CONTROL POINT
```

```
C   I=4:  THETAP=OUTER NORMAL DIRECTION AT P IN Y-Z PLANE,DEGREES
C   I=5:  XH=X-COORD OF HORSESHOE BOUND ELEMENT
C   I=6:  YH1=Y-COORD OF HORSESHOE CORNER (1)
C   I=7:  YH2=Y-COORD OF HORSESHOE CORNER (2)
C   I=8:  ZH1=Z-COORD OF HORSESHOE CORNER (1)
C   I=9:  ZH2=Z-COORD OF HORSESHOE CORNER (2)
C         WASH = VELOCITY INDUCED AT (P) IN DIRECTION OF OUTER NORMAL
C         (0 ALONG +Z ,90 ALONG +Y)
C*************************************************************************
      SUBROUTINE HSHOE (COORD,WASH)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/C1/  DELTAX,P8,P4,PI,MM,NN,M4
      DIMENSION COORD(20)
      XP=COORD(1)
      YP=COORD(2)
      ZP=COORD(3)
      THETAP=COORD(4)*.0174532900
      XH=COORD(5)
      YH1=COORD(6)
      YH2=COORD(7)
      ZH1=COORD(8)
      ZH2=COORD(9)
C   CALCULATE GEOM TERMS
      STP=DSIN(THETAP)
      CTP=DCOS(THETAP)
      R1=DSQRT((XH-XP)**2+(YH1-YP)**2+(ZH1-ZP)**2)
      CSB1=(XP-XH)/R1
      HT1=DSQRT((YH1-YP)**2+(ZH1-ZP)**2)
      IF (HT1.LE..00001D0) GO TO 15
C   CALCULATE DELTA-VEL DUE TO LEFT ELEMENT
      DTW1=(1.0D0+CSB1)/(HT1*P4)
C   RESOLVE DELTA-VEL COMPONENTS IN THETAP DIRECTION
      WNT1=DTW1*((ZP-ZH1)*(STP)+(YH1-YP)*(CTP))/HT1
      GO TO 18
15    CONTINUE
      WNT1=0.0D0
18    CONTINUE
      R2=DSQRT((XH-XP)**2+(YH2-YP)**2+(ZH2-ZP)**2)
      CSB2=(XP-XH)/R2
      HT2=DSQRT((YH2-YP)**2+(ZH2-ZP)**2)
      IF (HT2.LE..00001D0) GO TO 16
C   CALCULATE DELTA-VEL DUE TO RIGHT ELEMENT
      DTW2=(1.0D0+CSB2)/(HT2*P4)
C   RESOLVE DELTA-VEL COMPONENTS IN THETAP DIRECTION
      WNT2 = DTW2*((ZH2-ZP)*(STP)+(YP-YH2)*(CTP))/HT2
      GO TO 19
16    CONTINUE
      WNT2=0.0D0
```

```
19      CONTINUE
        RXSZ=(XH-XP)*(ZH2-ZH1)
        RXSY=(XH-XP)*(YH2-YH1)
        RYSZ=(YH1-YP)*(ZH2-ZH1)
        RZSY=(ZH1-ZP)*(YH2-YH1)
        S=DSQRT((YH2-YH1)**2+(ZH2-ZH1)**2)
        HS=DSQRT((RYSZ-RZSY)**2+(RXSZ)**2+(RXSY)**2)
        IF (HS.LE..000001D0) GO TO 30
C    FIND DELTA-VEL DUE TO BOUND ELEMENT
        DBW=((R1+R2)*(S**2-(R1-R2)**2)/(P8*HS**2*R1*R2))
C    RESOLVE DELTA-VEL COMPONENTS IN THETAP DIRECTION
        WNB = DBW*((-STP*RXSZ)+(CTP*RXSY))
        GO TO 40
30      CONTINUE
        WNB=0.0D0
40      CONTINUE
        WASH = WNB+WNT1+WNT2
        RETURN
        END
C*****************************************************************************
C    SUBROUTINE INVR(A,N,ISIZE)
C    SUBROUTINE INVR COMPUTES THE INVERSE OF THE INPUT MATRIX
C    (A).(A) IS DIMENSIONED ISIZE BY ISIZE AND CONTAINS N ROWS
C    AND N COLUMNS OF DATA.
C    SUBROUTINE INVR WAS OBTAINED FROM THE FOLLOWING REFERENCE SOURCE:
C    JOPPA,R.G.," WIND TUNNEL INTERFERENCE FACTORS FOR HIGH-
C    LIFT WINGS IN CLOSED WIND TUNNELS",NASA CR-2191,FEB. 1973.
C*****************************************************************************
        SUBROUTINE INVR(A,N,ISIZE)
        IMPLICIT REAL*8 (A-H,O-Z)
        DIMENSION  A(50,50),PIVOT(100)
        DIMENSION  IPIVOT(100),INDEX(100,2)
        EQUIVALENCE (AMAX,T,SWAP)
        EQUIVALENCE (IROW,JROW),(ICOLUM,JCOLUM)
100     DO 101 J=1,N
101     IPIVOT(J)=0
102     DO 550I=1,N
        AMAX=0.0D0
104     DO 105 J=1,N
106     IF (IPIVOT(J)-1)107,105,107
107     DO 120 K=1,N
108     IF (IPIVOT(K)-1) 109,120,740
109      IF (DABS(AMAX)-DABS(A(J,K))) 111,120,120
111     IROW=J
112     ICOLUM=K
113     AMAX=A(I,J)
120     CONTINUE
105     CONTINUE
```

```
110    IPIVOT(ICOLUM)=IPIVOT(ICOLUM)+1
130    IF (IROW-ICOLUM) 140,260,140
140    CONTINUE
150    DO 200 L=1,N
160    SWAP=A(IROW,L)
170    A(IROW,L)=A(ICOLUM,L)
200    A(ICOLUM,L)=SWAP
260    INDEX(I,1)=IROW
270    INDEX(I,2)=ICOLUM
310    PIVOT(I)=A(ICOLUM,ICOLUM)
330    A(ICOLUM,ICOLUM)=1.0
340    DO 350 L=1,N
350    A(ICOLUM,L)=A(ICOLUM,L)/PIVOT(I)
380    DO 550 L1=1,N
390    IF(L1-ICOLUM) 400,550,400
400    T=A(L1,ICOLUM)
420    A(L1,ICOLUM)=0.0
430    DO 450 L=1,N
450    A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
550    CONTINUE
600    DO 710 I=1,N
610    L=N+1-I
620    IF (INDEX(L,1)-INDEX(L,2)) 630,710,630
630    JROW=INDEX(L,1)
640    JCOLUM=INDEX(L,2)
650    DO 705 K=1,N
660    SWAP=A(K,JROW)
670    A(K,JROW)=A(K,JCOLUM)
700    A(K,JCOLUM)=SWAP
705    CONTINUE
710    CONTINUE
740    RETURN
       END
C*******************************************************************************
C   SUBROUTINE ELU TRI-DIAGONALIZES THE INPUT MATRIX (A).
C*******************************************************************************
       SUBROUTINE ELU(A,N,ND)
       IMPLICIT REAL*8(A-H,O-Z)
       DIMENSION A(ND,ND)
       NM1=N-1
       DO 100 K=1,NM1
       KP1=K+1
       DO 100 I=KP1,N
       G=-A(I,K)/A(K,K)
       A(I,K)=G
       DO 100 J=KP1,N
100    A(I,J)=A(I,J)+G*A(K,J)
       RETURN
```

```
      END
C*********************************************************************
C   SUBROUTINE SLVB SOLVES THE TRI-DIAGONALIZED MATRIX (A) OBTAINED
C   FROM ELU BY BACK SUBSTITUTION.
C*********************************************************************
      SUBROUTINE SLVB(A,N,ND,B)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(ND,ND),B(ND)
      NM1=N-1
      NP1=N+1
      DO 100 K=1,NM1
      KP1=K+1
      DO 100 I=KP1,N
100   B(I)=B(I)+A(I,K)*B(K)
      B(N)=B(N)/A(N,N)
      DO 300 K=2,N
      I=NP1-K
      J1=I+1
      DO 200 J=J1,N
200   B(I)=B(I)-A(I,J)*B(J)
300   B(I)=B(I)/A(I,I)
      RETURN
      END
C*********************************************************
C   SUBROUTINE LOOP (COORD, WASH)
C     FINDS INDUCED VELOCITY DUE TO A RECTANGULAR
C     VORTEX LOOP ELEMENT OF UNIT STRENGTH.
C
C          COORD(I) IS A 10 DIM. COLUMN VECTOR
C   I= 1:   XP=X-COORD OF CONTROL POINT
C   I= 2:   YP=Y-COORD OF CONTROL POINT
C   I= 3:   ZP=Z-COORD OF CONTROL POINT
C   I= 4: THETAP = OUTER NORMAL DIRECTION AT P IN Y-Z PLANE, DEGREES
C                 (0 ALONG +Z, 90 ALONG +Y)
C   I= 5: XH1=(XH2)=X-COORD OF CORNERS 1 AND 2
C   I= 6: XH3=(XH4)=X-COORD OF CORNERS 3 AND 4
C   I= 7: YH1=(YH4)=Y-COORD OF CORNERS 1 AND 4
C   I= 8: YH2=(YH3)=Y-COORD OF CORNERS 2 AND 3
C   I= 9: ZH1=(ZH4)=Z-COORD OF CORNERS 1 AND 4
C   I=10: ZH2=(ZH3)=Z-COORD OF CORNERS 2 AND 3
C
C        WASH = INDUCED VEL. AT (P) IN DIRECTION OF OUTER NORMAL
C*********************************************************
      SUBROUTINE LOOP (COORD,WASH)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/C1/  DELTAX,P8,P4,PI,MM,NN,M4
      DIMENSION COORD(20)
    1    XP=COORD(1)
```

```
            YP=COORD(2)
            ZP=COORD(3)
        THETAP=COORD(4)*0.01745329D0
           XH1=COORD(5)
           XH3=COORD(6)
           YH1=COORD(7)
           YH2=COORD(8)
           ZH1=COORD(9)
           ZH2=COORD(10)
C     FIND VALUES USED BY ALL FOUR PARTS OF VORTEX LOOP CALCS.
   10     STP=DSIN(THETAP)
          CTP=DCOS(THETAP)
           R1=DSQRT((XH1-XP)**2 + (YH1-YP)**2 + (ZH1-ZP)**2)
           R2=DSQRT((XH1-XP)**2 + (YH2-YP)**2 + (ZH2-ZP)**2)
           R3=DSQRT((XH3-XP)**2 + (YH2-YP)**2 + (ZH2-ZP)**2)
           R4=DSQRT((XH3-XP)**2 + (YH1-YP)**2 + (ZH1-ZP)**2)
C     FIND INDUCED VELOCITY DUE TO ELEMENT (1-2)
   20    RXSZ=(XH1-XP)*(ZH2-ZH1)
         RXSY=(XH1-XP)*(YH2-YH1)
         RYSZ=(YH1-YP)*(ZH2-ZH1)
         RZSY=(ZH1-ZP)*(YH2-YH1)
            S=DSQRT((YH2-YH1)**2 + (ZH2-ZH1)**2)
           HS=DSQRT((RYSZ-RZSY)**2 + (RXSZ)**2 + (RXSY)**2)
         IF(HS.LE.0.00001D0) GO TO 25
         CBW1=((R1+R2)*(S**2 -(R1-R2)**2)/(P8*HS**2*R1*R2))
         WNB1=CBW1*((-STP*RXSZ) + (CTP*RXSY))
         GO TO 30
   25    WNB1=0.0D0
C     FIND INDUCED VELOCITY DUE TO ELEMENT (2-3)
   30     HT2=DSQRT((YH2-YP)**2 + (ZH2-ZP)**2)
         IF(HT2.LE.0.00001D0) GO TO 35
         CSB2=(XP-XH1)/R2
         CSB3=(XH3-XP)/R3
         CTW2=(CSB2+CSB3)/(P4*HT2)
         WNT2=CTW2*((ZH2-ZP)*STP + (YP-YH2)*CTP)/HT2
         GO TO 40
   35    WNT2=0.0D0
C     FIND INDUCED VELOCITY DUE TO ELEMENT (3-4)
   40    RXSZ=(XH3-XP)*(ZH1-ZH2)
         RXSY=(XH3-XP)*(YH1-YH2)
         RYSZ=(YH2-YP)*(ZH1-ZH2)
         RZSY=(ZH2-ZP)*(YH1-YH2)
            S=DSQRT((YH2-YH1)**2 + (ZH2-ZH1)**2)
           HS=DSQRT((RYSZ-RZSY)**2 + (RXSZ)**2 + (RXSY)**2)
         IF(HS.LE.0.00001D0) GO TO 45
         CBW3=((R3+R4)*(S**2 - (R3-R4)**2)/(P8*HS**2*R3*R4))
         WNB3=CBW3*((-STP*RXSZ) + (CTP*RXSY))
         GO TO 50
```

```
   45  WNB3=0.0DO
C    FIND INDUCED VELOCITY DUE TO ELEMENT (4-1)
   50    HT4=DSQRT((YH1-YP)**2 + (ZH1-ZP)**2)
         IF(HT4.LE.0.0000100) GO TO 55
         CSB1=(XP-XH1)/R1
         CSB4=(XH3-XP)/R4
         CTW4=(CSB1+CSB4)/(P4*HT4)
         WNT4=CTW4*((ZP-ZH1)*STP + (YH1-YP)*CTP)/HT4
         GO TO 60
   55    WNT4=0.0DO
C    SUM UP INDUCED VELOCITY INCREMENTS.
   60    WASH=WNB1 + WNT2 + WNB3 + WNT4
         RETURN
         END
C*********************************************************************
C    SUBROUTINE DQTFG
C
C
C    COMPUTES THE VECTOR OF INTEGRAL VALUES FOR A GIVEN
C    GENERAL TABLE OF ARGUMENT AND FUNCTION VALUES.
C    Y: INPUT VECTOR OF FUNCTION VALUES.
C    X: INPUT VECTOR OF ARGUMENT VALUES.
C    Z: RESULTING VECTOR OF INTEGRAL VALUES.
C
C    BEGINNING WITH Z(1)=0,EVALUATION OF VECTOR Z IS DONE BY
C    MEANS OF TRAPEZOIDAL RULE (SECOND ORDER FORMULA).
C    SUBROUTINE DQTFG WAS OBTAINED FROM THE NPS SOURCE
C    LIBRARY.
C*********************************************************************
      SUBROUTINE DQTFG(X,Y,Z,NDIM)
C
C
      DIMENSION X(NDIM),Y(NDIM),Z(NDIM)
      DOUBLE PRECISION X,Y,Z,SUM1,SUM2
C
      SUM2=0.DO
      IF(NDIM-1)4,3,1
C
C     INTEGRATION LOOP
    1 DO 2 I=2,NDIM
      SUM1=SUM2
      SUM2=SUM2+.5DO*(X(I)-X(I-1))*(Y(I)+Y(I-1))
    2 Z(I-1)=SUM1
    3 Z(NDIM)=SUM2
    4 RETURN
      END
```

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